

METHODS FOR DETECTING DELETIONS AND DUPLICATIONS OF CHROMOSOME SEGMENTS

FIELD OF THE INVENTION

[001] The present invention generally relates to methods of detecting deletions and duplications of chromosome segments or entire chromosomes.

BACKGROUND OF THE INVENTION

[002] Copy number variation (CNV) has been identified as a major cause of structural variation in the genome, involving both duplications and deletions of sequences that typically range in length from 1,000 base pairs (1 kb) to 20 megabases (mb). Deletions and duplications of chromosome segments or entire chromosomes are associated with a variety of conditions, such as susceptibility or resistance to disease.

[003] CNVs are often assigned to one of two main categories, based on the length of the affected sequence. The first category includes copy number polymorphisms (CNPs), which are common in the general population, occurring with an overall frequency of greater than 1%. CNPs are typically small (most are less than 10 kilobases in length), and they are often enriched for genes that encode proteins important in drug detoxification and immunity. A subset of these CNPs is highly variable with respect to copy number. As a result, different human chromosomes can have a wide range of copy numbers (*e.g.*, 2, 3, 4, 5, *etc.*) for a particular set of genes. CNPs associated with immune response genes have recently been associated with susceptibility to complex genetic diseases, including psoriasis, Crohn's disease, and glomerulonephritis.

[004] The second class of CNVs includes relatively rare variants that are much longer than CNPs, ranging in size from hundreds of thousands of base pairs to over 1 million base pairs in length. In some cases, these CNVs may have arisen during production of the sperm or egg that gave rise to a particular individual, or they may have been passed down for only a few generations within a family. These large and rare structural variants have been observed disproportionately in subjects with mental retardation, developmental delay, schizophrenia, and autism. Their appearance in such subjects has led to speculation that large and rare CNVs may be more important in neurocognitive diseases than other forms of inherited mutations, including single nucleotide substitutions.

[005] Gene copy number can be altered in cancer cells. For instance, duplication of Chr1p is common in breast cancer, and the EGFR copy number can be higher than normal in non-small cell lung cancer. Cancer is one of the leading causes of death; thus, early diagnosis and treatment of cancer is important, since it can improve the patient's outcome (such as by increasing the probability of remission and the duration of remission). Early diagnosis can also allow the patient to undergo fewer or less drastic treatment alternatives. Many of the current treatments that destroy cancerous cells also affect normal cells, resulting in a variety of possible side-effects, such as nausea, vomiting, low blood cell counts, increased risk of infection, hair loss, and ulcers in mucous membranes. Thus, early detection of cancer is desirable since it can reduce the amount and/or number of treatments (such as chemotherapeutic agents or radiation) needed to eliminate the cancer.

[006] Copy number variation has also been associated with severe mental and physical handicaps, and idiopathic learning disability. Non-invasive prenatal testing (NIPT) using cell-free DNA (cfDNA) can be used to detect abnormalities, such as fetal trisomies 13, 18, and 21, triploidy, and sex chromosome aneuploidies. Subchromosomal microdeletions, which can also result in severe mental and physical handicaps, are more challenging to detect due to their smaller size. Eight of the microdeletion syndromes have an aggregate incidence of more than 1 in 1000, making them nearly as common as fetal autosomal trisomies.

[007] In addition, a higher copy number of CCL3L1 has been associated with lower susceptibility to HIV infection, and a low copy number of FCGR3B (the CD16 cell surface immunoglobulin receptor) can increase susceptibility to systemic lupus erythematosus and similar inflammatory autoimmune disorders.

[008] Thus, improved methods are needed to detect deletions and duplications of chromosome segments or entire chromosomes. Preferably, these methods can be used to more accurately diagnose disease or an increased risk of disease, such as cancer or CNVs in a gestating fetus.

SUMMARY OF THE INVENTION

[009] In one aspect, the invention features a method of determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in the genome of one or more cells from an individual. In some embodiments, the method includes obtaining phased genetic data

for the first homologous chromosome segment comprising, the identity of the allele present at that locus on the first homologous chromosome segment for each locus in a set of polymorphic loci on the first homologous chromosome segment, obtaining phased genetic data for the second homologous chromosome segment comprising the identity of the allele present at that locus on the second homologous chromosome segment for each locus in the set of polymorphic loci on the second homologous chromosome segment, and obtaining measured genetic allelic data comprising the amount of each allele present in a sample of DNA or RNA from one or more cells from the individual , for each of the alleles at each of the loci in the set of polymorphic loci. In some embodiments, the method includes enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment in the genome of one or more cells from the individual, calculating (such as calculating on a computer) a likelihood of one or more of the hypotheses based on the obtained genetic data of the sample and the obtained phased genetic data, and selecting the hypothesis with the greatest likelihood, thereby determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment in the genome of one or more cells from the individual.

[0010] In one aspect, the invention provides a method for determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in the genome of one or more cells from an individual. In some embodiments, the method includes obtaining phased genetic data for the first homologous chromosome segment comprising the identity of the allele present at that locus on the first homologous chromosome segment for each locus in a set of polymorphic loci on the first homologous chromosome segment, obtaining phased genetic data for the second homologous chromosome segment comprising the identity of the allele present at that locus on the second homologous chromosome segment for each locus in the set of polymorphic loci on the second homologous chromosome segment, and obtaining measured genetic allelic data comprising the amount of each allele present in a sample of DNA or RNA from one or more cells from the individual for each of the alleles at each of the loci in the set of polymorphic loci. In some embodiments, the method includes enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment; calculating, for each of the hypotheses, expected genetic data for the plurality of loci in the sample from the obtained phased genetic data; calculating (such as calculating on a computer)

the data fit between the obtained genetic data of the sample and the expected genetic data for the sample; ranking one or more of the hypotheses according to the data fit; and selecting the hypothesis that is ranked the highest, thereby determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment in the genome of one or more cells from the individual.

[0011] In one aspect, the invention features a method for determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in the genome of one or more cells from an individual. In some embodiments, the method includes obtaining phased genetic data for the first homologous chromosome segment comprising the identity of the allele present at that locus on the first homologous chromosome segment for each locus in a set of polymorphic loci on the first homologous chromosome segment, obtaining phased genetic data for the second homologous chromosome segment comprising the identity of the allele present at that locus on the second homologous chromosome segment for each locus in the set of polymorphic loci on the second homologous chromosome segment, and obtaining measured genetic allelic data comprising, for each of the alleles at each of the loci in the set of polymorphic loci, the amount of each allele present in a sample of DNA or RNA from one or more target cells and one or more non-target cells from the individual. In some embodiments, the method includes enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment; calculating (such as calculating on a computer), for each of the hypotheses, expected genetic data for the plurality of loci in the sample from the obtained phased genetic data for one or more possible ratios of DNA or RNA from the one or more target cells to the total DNA or RNA in the sample; calculating (such as calculating on a computer) for each possible ratio of DNA or RNA and for each hypothesis, the data fit between the obtained genetic data of the sample and the expected genetic data for the sample for that possible ratio of DNA or RNA and for that hypothesis; ranking one or more of the hypotheses according to the data fit; and selecting the hypothesis that is ranked the highest, thereby determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment in the genome of one or more cells from the individual.

[0012] In one aspect, the invention features a method for determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as

compared to a second homologous chromosome segment in the genome of one or more cells from an individual. In some embodiments, the method includes obtaining phased genetic data for the first homologous chromosome segment comprising the identity of the allele present at that locus on the first homologous chromosome segment for each locus in a set of polymorphic loci on the first homologous chromosome segment, obtaining phased genetic data for the second homologous chromosome segment comprising the identity of the allele present at that locus on the second homologous chromosome segment for each locus in the set of polymorphic loci on the second homologous chromosome segment, and obtaining measured genetic allelic data comprising the amount of each allele present in a sample of DNA or RNA from one or more target cells and one or more non-target cells from the individual for each of the alleles at each of the loci in the set of polymorphic loci. In some embodiments, the method includes enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment; calculating (such as calculating on a computer), for each of the hypotheses, expected genetic data for the plurality of loci in the sample from the obtained phased genetic data for one or more possible ratios of DNA or RNA from the one or more target cells to the total DNA or RNA in the sample; calculating (such as calculating on a computer) for each locus in the plurality of loci, each possible ratio of DNA or RNA, and each hypothesis, the likelihood that the hypothesis is correct by comparing the obtained genetic data of the sample for that locus and the expected genetic data for that locus for that possible ratio of DNA or RNA and for that hypothesis; determining the combined probability for each hypothesis by combining the probabilities of that hypothesis for each locus and each possible ratio; and selecting the hypothesis with the greatest combined probability, thereby determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment.

[0013] In one aspect, the invention features a method for determining a number of copies of a chromosome segment of interest in the genome of a fetus. In some embodiments, the method includes obtaining phased genetic data for at least one biological parent of the fetus, wherein the phased genetic data comprises the identity of the allele present for each locus in a set of polymorphic loci on a first homologous chromosome segment and a second homologous chromosome segment in a pair of homologous chromosome segments that comprises the chromosome segment of interest. In some embodiments, the method includes obtaining genetic data at the set of polymorphic loci on the chromosome segment of

interest in a mixed sample of DNA or RNA comprising fetal DNA or RNA and maternal DNA or RNA from the mother of the fetus by measuring the quantity of each allele at each locus. In some embodiments, the method includes enumerating a set of one or more hypotheses specifying the number of copies of the chromosome segment of interest present in the genome of the fetus. In some embodiments, the method includes enumerating a set of one or more hypotheses specifying, for one or both parents, the number of copies of the first homologous chromosome segment or portion thereof from the parent in the genome of the fetus, the number of copies of the second homologous chromosome segment or portion thereof from the parent in the genome of the fetus, and the total number of copies of the chromosome segment of interest present in the genome of the fetus. In some embodiments, the method includes calculating (such as calculating on a computer), for each of the hypotheses, expected genetic data for the plurality of loci in the mixed sample from the obtained phased genetic data from the parent(s); calculating (such as calculating on a computer) the data fit between the obtained genetic data of the mixed sample and the expected genetic data for the mixed sample; ranking one or more of the hypotheses according to the data fit; and selecting the hypothesis that is ranked the highest, thereby determining the number of copies of the chromosome segment of interest in the genome of the fetus.

[0014] In one aspect, the invention features a method for determining a number of copies of a chromosome or chromosome segment of interest in the genome of a fetus. In some embodiments, the method includes obtaining phased genetic data for at least one biological parent of the fetus, wherein the phased genetic data comprises the identity of the allele present for each locus in a set of polymorphic loci on a first homologous chromosome segment and a second homologous chromosome segment in the parent. In some embodiments, the method includes obtaining genetic data at the set of polymorphic loci on the chromosome or chromosome segment in a mixed sample of DNA or RNA comprising fetal DNA or RNA and maternal DNA or RNA from the mother of the fetus by measuring the quantity of each allele at each locus. In some embodiments, the method includes enumerating a set of one or more hypotheses specifying the number of copies of the chromosome or chromosome segment of interest present in the genome of the fetus. In some embodiments, the method includes creating (such as creating on a computer) for each of the hypotheses, a probability distribution of the expected quantity of each allele at each of the plurality of loci in mixed sample from the (i) the

obtained phased genetic data from the parent(s) and (ii) optionally the probability of one or more crossovers that may have occurred during the formation of a gamete that contributed a copy of the chromosome or chromosome segment of interest to the fetus; calculating (such as calculating on a computer) a fit, for each of the hypotheses, between (1) the obtained genetic data of the mixed sample and (2) the probability distribution of the expected quantity of each allele at each of the plurality of loci in mixed sample for that hypothesis; ranking one or more of the hypotheses according to the data fit; and selecting the hypothesis that is ranked the highest, thereby determining the number of copies of the chromosome segment of interest in the genome of the fetus.

[0015] In some embodiments, the method includes obtaining phased genetic data for the mother of the fetus. In some embodiments, the method includes enumerating a set of one or more hypotheses specifying the number of copies of the first homologous chromosome segment or portion thereof from the mother in the genome of the fetus, the number of copies of the second homologous chromosome segment or portion thereof from the mother in the genome of the fetus, and the total number of copies of the chromosome segment of interest present in the genome of the fetus. In some embodiments, the method includes calculating, for each of the hypotheses, expected genetic data for the plurality of loci in the mixed sample from the obtained phased genetic data from the mother.

[0016] In some embodiments, the expected genetic data for each of the hypotheses comprises the identity and an amount of one or more alleles at each locus in the plurality of loci from the maternal DNA or RNA and fetal DNA or RNA in the mixed sample. In some embodiments, the method includes calculating (such as calculating on a computer) expected genetic data by determining a fraction of fetal DNA or RNA and a fraction of maternal DNA or RNA in the mixed sample. In some embodiments, the method includes calculating, for each locus in the plurality of loci, the expected amount of one or more of the alleles for that locus in the maternal DNA or RNA in the mixed sample using the identity of the allele(s) present at that locus in the obtained phased genetic data of the mother and the fraction of maternal DNA or RNA in the mixed sample. In some embodiments, the method includes calculating (such as calculating on a computer), for each locus in the plurality of loci for each hypothesis, the expected amount of one or more of the alleles for that locus in the fetal DNA or RNA inherited from the mother in the mixed sample using the identity of the allele present at that locus in the first or second

homologous chromosome segment from the mother that is specified by the hypothesis to have been inherited by the fetus, the number of copies of the first or second homologous chromosome segment from the mother that is specified by the hypothesis to have been inherited by the fetus, and the fraction of fetal DNA or RNA in the mixed sample.

[0017] In some embodiments, the expected genetic data for each of the hypotheses comprises the identity and an amount of one or more alleles at each locus in the plurality of loci from the maternal DNA or RNA and fetal DNA or RNA in the mixed sample. In some embodiments, the method includes calculating expected genetic data by determining a fraction of fetal DNA or RNA and a fraction of maternal DNA or RNA in the mixed sample. In some embodiments, the method includes calculating (such as calculating on a computer), for each locus in the plurality of loci, the expected amount of one or more of the alleles for that locus in the maternal DNA or RNA in the mixed sample using the identity of the allele(s) present at that locus in the obtained phased genetic data of the mother and the fraction of maternal DNA or RNA in the mixed sample. In some embodiments, the method includes calculating (such as calculating on a computer), for each locus in the plurality of loci for each hypothesis, the expected amount of one or more of the alleles for that locus in the fetal DNA or RNA inherited from the mother in the mixed sample using the identity of the allele present at that locus in the first or second homologous chromosome segment from the mother that is specified by the hypothesis to have been inherited by the fetus, the number of copies of the first or second homologous chromosome segment from the mother that is specified by the hypothesis to have been inherited by the fetus, the identity of one or more possible alleles at that locus in the first or second homologous chromosome segment from the father that is specified by the hypothesis to have been inherited by the fetus, the number of copies of the first or second homologous chromosome segment from the father that is specified by the hypothesis to have been inherited by the fetus, and the fraction of fetal DNA or RNA in the mixed sample. In some embodiments, population frequencies are used to predict the identity of the alleles in the first or second homologous chromosome segment from the father. In some embodiments, the probability for each of the possible alleles at each locus in the first or second homologous chromosome segment from the father are considered to be the same.

[0018] In some embodiments, the method includes obtaining phased genetic data for both the mother and father of the fetus. In some embodiments, the method includes enumerating a set of

one or more hypotheses specifying the number of copies of the first homologous chromosome segment or portion thereof from the mother in the genome of the fetus, the number of copies of the second homologous chromosome segment or portion thereof from the mother in the genome of the fetus, the number of copies of the first homologous chromosome segment or portion thereof from the father in the genome of the fetus, the number of copies of the second homologous chromosome segment or portion thereof from the father in the genome of the fetus, and the total number of copies of the chromosome segment of interest present in the genome of the fetus. In some embodiments, the method includes calculating (such as calculating on a computer), for each of the hypotheses, expected genetic data for the plurality of loci in the mixed sample from the obtained phased genetic data from the mother and obtained phased genetic data from the father.

[0019] In some embodiments, the expected genetic data for each of the hypotheses comprises the identity and an amount of one or more alleles at each locus in the plurality of loci from the maternal DNA or RNA and fetal DNA or RNA in the mixed sample. In some embodiments, the method includes calculating expected genetic data by determining a fraction of fetal DNA or RNA and a fraction of maternal DNA or RNA in the mixed sample. In some embodiments, the method includes calculating (such as calculating on a computer), for each locus in the plurality of loci, the expected amount of one or more of the alleles for that locus in the maternal DNA or RNA in the mixed sample using the identity of the allele(s) present at that locus in the obtained phased genetic data of the mother and the fraction of maternal DNA or RNA in the mixed sample. In some embodiments, the method includes calculating (such as calculating on a computer), for each locus in the plurality of loci for each hypothesis, the expected amount of one or more of the alleles for that locus in the fetal DNA or RNA in the mixed sample using the identity of the allele present at that locus in the first or second homologous chromosome segment from the mother that is specified by the hypothesis to have been inherited by the fetus, the number of copies of the first or second homologous chromosome segment from the mother that is specified by the hypothesis to have been inherited by the fetus, the identity of the allele present at that locus in the first or second homologous chromosome segment from the father that is specified by the hypothesis to have been inherited by the fetus, the number of copies of the first or second homologous chromosome segment from the father that is specified by the hypothesis to have been inherited by the fetus, and the fraction of fetal DNA or RNA in the mixed sample.

[0020] In some embodiments, the method includes calculating (such as calculating on a computer), for each of the hypotheses, a probability distribution of expected genetic data for the plurality of loci in the mixed sample from the obtained phased genetic data from the parent(s). In some embodiments, the method includes increasing the probability in the probability distribution of an a particular allele being present at a first locus in the mixed sample if that particular allele is present in the first homologous segment in the parent and an allele at a nearby locus in the first homologous segment in the parent is observed in the obtained genetic data of the mixed sample; or decreasing the probability in the probability distribution of an a particular allele being present at a first locus in the mixed sample if that particular allele is present in the first homologous segment in the parent and an allele at a nearby locus in the first homologous segment in the parent is not observed in the obtained genetic data of the mixed sample. In some embodiments, the method includes increasing the probability in the probability distribution of an a particular allele being present at a second locus in the mixed sample if that particular allele is present in the second homologous segment in the parent and an allele at a nearby locus in the second homologous segment in the parent is observed in the obtained genetic data of the mixed sample; or decreasing the probability in the probability distribution of an a particular allele being present at a second locus in the mixed sample if that particular allele is present in the second homologous segment in the parent and an allele at a nearby locus in the second homologous segment in the parent is not observed in the obtained genetic data of the mixed sample.

[0021] In some embodiments, the method includes obtaining phased genetic data for both the mother and father of the fetus. In some embodiments, the method includes enumerating a set of one or more hypotheses specifying the number of copies of the first homologous chromosome segment or portion thereof from the mother in the genome of the fetus, the number of copies of the second homologous chromosome segment or portion thereof from the mother in the genome of the fetus, the number of copies of the first homologous chromosome segment or portion thereof from the father in the genome of the fetus, the number of copies of the second homologous chromosome segment or portion thereof from the father in the genome of the fetus, and the total number of copies of the chromosome segment of interest present in the genome of the fetus. In some embodiments, the method includes calculating (such as calculating on a computer), for each of the hypotheses, a probability distribution of expected genetic data for the plurality of loci in the mixed sample from the obtained phased genetic data from the mother and

father. In some embodiments, the method includes increasing the probability in the probability distribution of an a particular allele being present at a first locus in the mixed sample if that particular allele is present in the first homologous segment in the mother or father and an allele at a nearby locus in the first homologous segment in that parent is observed in the obtained genetic data of the mixed sample; or decreasing the probability in the probability distribution of an a particular allele being present at a first locus in the mixed sample if that particular allele is present in the first homologous segment in the mother or father and an allele at a nearby locus in the first homologous segment in that parent is not observed in the obtained genetic data of the mixed sample. In some embodiments, the method includes increasing the probability in the probability distribution of an a particular allele being present at a second locus in the mixed sample if that particular allele is present in the second homologous segment in the mother or father and an allele at a nearby locus in the second homologous segment in that parent is observed in the obtained genetic data of the mixed sample; or decreasing the probability in the probability distribution of an a particular allele being present at a second locus in the mixed sample if that particular allele is present in the second homologous segment in the mother or father and an allele at a nearby locus in the second homologous segment in that parent is not observed in the obtained genetic data of the mixed sample.

[0022] In some embodiments, the first locus and the locus that is nearby to the first locus co-segregate. In some embodiments, the second locus and the locus that is nearby to the second locus co-segregate. In some embodiments, no crossovers are expected to occur between the first locus and the locus that is nearby to the first locus. In some embodiments, no crossovers are expected to occur between the second locus and the locus that is nearby to the second locus. In some embodiments, the distance between the first locus and the locus that is nearby to the first locus is less than 5 mb, 1 mb, 100 kb, 10 kb, 1 kb, 0.1 kb, or 0.01 kb. In some embodiments, the distance between the second locus and the locus that is nearby to the second locus is less than 5 mb, 1 mb, 100 kb, 10 kb, 1 kb, 0.1 kb, or 0.01 kb.

[0023] In some embodiments, one or more crossovers occurs during the formation of a gamete that contributed a copy of the chromosome segment of interest to the fetus; and the crossover produces a chromosome segment of interest in the genome of the fetus that comprises a portion of the first homologous segment and a portion of the second homologous segment from the parent. In some embodiments, the set of hypothesis comprises one or more hypotheses

specifying the number of copies of the chromosome segment of interest in the genome of the fetus that comprises a portion of the first homologous segment and a portion of the second homologous segment from the parent.

[0024] In some embodiments, the expected genetic data of the mixed sample comprises the expected amount of one or more of the alleles at each locus in the plurality of loci in the mixed sample for each of the hypotheses.

[0025] In one aspect, the invention features a method of determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in the genome of an individual (such as in the genome of one or more cells, cfDNA, cfRNA, an individual suspected of having cancer, a fetus, or an embryo) using phased genetic data. In some embodiments, the method involves simultaneously or sequentially in any order (i) obtaining phased genetic data for the first homologous chromosome segment comprising the identity of the allele present at that locus on the first homologous chromosome segment for each locus in a set of polymorphic loci on the first homologous chromosome segment, (ii) obtaining phased genetic data for the second homologous chromosome segment comprising the identity of the allele present at that locus on the second homologous chromosome segment for each locus in the set of polymorphic loci on the second homologous chromosome segment, and (iii) obtaining measured genetic allelic data comprising the amount of each allele at each of the loci in the set of polymorphic loci in a sample of DNA or RNA from one or more cells from the individual or in a mixed sample of cell-free DNA or RNA from two or more genetically different cells from the individual. In some embodiments, the method involves calculating allele ratios for one or more loci in the set of polymorphic loci that are heterozygous in at least one cell from which the sample was derived. In some embodiments, the calculated allele ratio for a particular locus is the measured quantity of one of the alleles divided by the total measured quantity of all the alleles for the locus. In some embodiments, the method involves determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment by comparing one or more calculated allele ratios for a locus to an expected allele ratio, such as a ratio that is expected for that locus if the first and second homologous chromosome segments are present in equal proportions. In some embodiments, the expected ratio is 0.5 for biallelic loci.

[0026] In some embodiments for prenatal testing, the method involves simultaneously or sequentially in any order (i) obtaining phased genetic data for the first homologous chromosome segment in the genome of a fetus (such as a fetus gestating in a pregnant mother) comprising the identity of the allele present at that locus on the first homologous chromosome segment for each locus in a set of polymorphic loci on the first homologous chromosome segment, (ii) obtaining phased genetic data for the second homologous chromosome segment in the genome of the fetus comprising the identity of the allele present at that locus on the second homologous chromosome segment for each locus in the set of polymorphic loci on the second homologous chromosome segment, and (iii) obtaining measured genetic allelic data comprising the amount of each allele at each of the loci in the set of polymorphic loci in a mixed sample of DNA or RNA from the mother of the fetus that includes fetal DNA or RNA and maternal DNA or RNA (such as a mixed sample of cell-free DNA or RNA originating from a blood sample from the mother that includes fetal cell-free DNA or RNA and maternal cell-free DNA or RNA). In some embodiments, the method involves calculating allele ratios for one or more loci in the set of polymorphic loci that are heterozygous in the fetus and/or heterozygous in the mother. In some embodiments, the calculated allele ratio for a particular locus is the measured quantity of one of the alleles divided by the total measured quantity of all the alleles for the locus. In some embodiments, the method involves determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment by comparing one or more calculated allele ratios for a locus to an expected allele ratio, such as a ratio that is expected for that locus if the first and second homologous chromosome segments are present in equal proportions.

[0027] In some embodiments, a calculated allele ratio is indicative of an overrepresentation of the number of copies of the first homologous chromosome segment if either (i) the allele ratio for the measured quantity of the allele present at that locus on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus is greater than the expected allele ratio for that locus, or (ii) the allele ratio for the measured quantity of the allele present at that locus on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than the expected allele ratio for that locus. In some embodiments, a calculated allele ratio is indicative of no overrepresentation of the number of copies of the first homologous chromosome segment if either (i) the allele ratio for the measured quantity of the allele present at that locus on the first homologous chromosome divided by the

total measured quantity of all the alleles for the locus is less than or equal to the expected allele ratio for that locus, or (ii) the allele ratio for the measured quantity of the allele present at that locus on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is greater than or equal to the expected allele ratio for that locus.

[0028] In some embodiments, determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment includes enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment. In some embodiments, predicted allele ratios for the loci that are heterozygous in at least one cell (such as the loci that are heterozygous in the fetus and/or heterozygous in the mother) are estimated for each hypothesis given the degree of overrepresentation specified by that hypothesis. In some embodiments, the likelihood that the hypothesis is correct is calculated by comparing the calculated allele ratios to the predicted allele ratios, and the hypothesis with the greatest likelihood is selected. In some embodiments, an expected distribution of a test statistic is calculated using the predicted allele ratios for each hypothesis. In some embodiments, the likelihood that the hypothesis is correct is calculated by comparing a test statistic that is calculated using the calculated allele ratios to the expected distribution of the test statistic that is calculated using the predicted allele ratios, and the hypothesis with the greatest likelihood is selected. In some embodiments, predicted allele ratios for the loci that are heterozygous in at least one cell (such as the loci that are heterozygous in the fetus and/or heterozygous in the mother) are estimated given the phased genetic data for the first homologous chromosome segment, the phased genetic data for the second homologous chromosome segment, and the degree of overrepresentation specified by that hypothesis. In some embodiments, the likelihood that the hypothesis is correct is calculated by comparing the calculated allele ratios to the predicted allele ratios; and the hypothesis with the greatest likelihood is selected.

[0029] In some embodiments, the ratio of DNA (or RNA) from one or more target cells to the total DNA (or RNA) in the sample is calculated. An exemplary ratio is the ratio of fetal DNA (or RNA) to the total DNA (or RNA) in the sample. In some embodiments, the ratio of fetal DNA to total DNA in the sample is determined by measuring the amount of an allele at one or more loci in which the fetus has the allele and the mother does not have the allele. In some embodiments, the ratio of fetal DNA to total DNA in the sample is determined by measuring the difference in methylation between one or more maternal and fetal alleles. In some embodiments,

a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment are enumerated. In some embodiments, predicted allele ratios for the loci that are heterozygous in at least one cell (such as the loci that are heterozygous in the fetus and/or heterozygous in the mother) are estimated given the calculated ratio of DNA or RNA and the degree of overrepresentation specified by that hypothesis are estimated for each hypothesis. In some embodiments, the likelihood that the hypothesis is correct is calculated by comparing the calculated allele ratios to the predicted allele ratios, and the hypothesis with the greatest likelihood is selected. In some embodiments, an expected distribution of a test statistic calculated using the predicted allele ratios and the calculated ratio of DNA or RNA is estimated for each hypothesis. In some embodiments, the likelihood that the hypothesis is correct is determined by comparing a test statistic calculated using the calculated allele ratios and the calculated ratio of DNA or RNA to the expected distribution of the test statistic calculated using the predicted allele ratios and the calculated ratio of DNA or RNA, and the hypothesis with the greatest likelihood is selected.

In some embodiments, the method includes enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment. In some embodiments, the method includes estimating, for each hypothesis, either (i) predicted allele ratios for the loci that are heterozygous in at least one cell (such as the loci that are heterozygous in the fetus and/or heterozygous in the mother) given the degree of overrepresentation specified by that hypothesis or (ii) for one or more possible ratios of DNA or RNA (such as ratios of fetal DNA or RNA to the total DNA or RNA in the sample), an expected distribution of a test statistic calculated using the predicted allele ratios and the possible ratio of DNA or RNA from the one or more target cells (such as fetal cells) to the total DNA or RNA in the sample. In some embodiments, a data fit is calculated by comparing either (i) the calculated allele ratios to the predicted allele ratios, or (ii) a test statistic calculated using the calculated allele ratios and the possible ratio of DNA or RNA to the expected distribution of the test statistic calculated using the predicted allele ratios and the possible ratio of DNA or RNA. In some embodiments, one or more of the hypotheses are ranked according to the data fit, and the hypothesis that is ranked the highest is selected. In some embodiments, a technique or algorithm, such as a search algorithm, is used for one or more of the following steps: calculating the data fit, ranking the hypotheses, or selecting the

hypothesis that is ranked the highest. In some embodiments, the data fit is a fit to a beta-binomial distribution or a fit to a binomial distribution. In some embodiments, the technique or algorithm is selected from the group consisting of maximum likelihood estimation, maximum a-posteriori estimation, Bayesian estimation, dynamic estimation (such as dynamic Bayesian estimation), and expectation-maximization estimation. In some embodiments, the method includes applying the technique or algorithm to the obtained genetic data and the expected genetic data.

[0030] In some embodiments, the method includes creating a partition of possible ratios (such as ratios of fetal DNA or RNA to the total DNA or RNA in the sample) that range from a lower limit to an upper limit for the ratio of DNA or RNA from the one or more target cells to the total DNA or RNA in the sample. In some embodiments, a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment are enumerated. In some embodiments, the method includes estimating, for each of the possible ratios of DNA or RNA in the partition and for each hypothesis, either (i) predicted allele ratios for the loci that are heterozygous in at least one cell (such as the loci that are heterozygous in the fetus and/or heterozygous in the mother) given the possible ratio of DNA or RNA and the degree of overrepresentation specified by that hypothesis or (ii) an expected distribution of a test statistic calculated using the predicted allele ratios and the possible ratio of DNA or RNA. In some embodiments, the method includes calculating, for each of the possible ratios of DNA or RNA in the partition and for each hypothesis, the likelihood that the hypothesis is correct by comparing either (i) the calculated allele ratios to the predicted allele ratios, or (ii) a test statistic calculated using the calculated allele ratios and the possible ratio of DNA or RNA to the expected distribution of the test statistic calculated using the predicted allele ratios and the possible ratio of DNA or RNA. In some embodiments, the combined probability for each hypothesis is determined by combining the probabilities of that hypothesis for each of the possible ratios in the partition; and the hypothesis with the greatest combined probability is selected. In some embodiments, the combined probability for each hypothesis is determining by weighting the probability of a hypothesis for a particular possible ratio based on the likelihood that the possible ratio is the correct ratio.

[0031] In one aspect, the invention features a method for determining a number of copies of a chromosome or chromosome segment in the genome of one or more cells from an individual

using phased or unphased genetic data. In some embodiments, the method involves obtaining genetic data at a set of polymorphic loci on the chromosome or chromosome segment in a sample by measuring the quantity of each allele at each locus. In some embodiments, the sample is a sample of DNA or RNA from one or more cells from the individual or a mixed sample of cell-free DNA from the individual that includes cell-free DNA from two or more genetically different cells. In some embodiments, allele ratios are calculated for the loci that are heterozygous in at least one cell from which the sample was derived. In some embodiments, the calculated allele ratio for a particular locus is the measured quantity of one of the alleles divided by the total measured quantity of all the alleles for the locus. In some embodiments, the calculated allele ratio for a particular locus is the measured quantity of one of the alleles (such as the allele on the first homologous chromosome segment) divided by the measured quantity of one or more other alleles (such as the allele on the second homologous chromosome segment) for the locus. In some embodiments, a set of one or more hypotheses specifying the number of copies of the chromosome or chromosome segment in the genome of one or more of the cells are enumerated. In some embodiments, the hypothesis that is most likely based on the test statistic is selected, thereby determining the number of copies of the chromosome or chromosome segment in the genome of one or more of the cells.

[0032] In one aspect, the invention features a method for determining a number of copies of a chromosome or chromosome segment in the genome of a fetus (such as a fetus that is gestating in a pregnant mother) using phased or unphased genetic data. In some embodiments, the method involves obtaining genetic data at a set of polymorphic loci on the chromosome or chromosome segment in a sample by measuring the quantity of each allele at each locus. In some embodiments, the sample is a mixed sample of DNA comprising fetal DNA or RNA and maternal DNA or RNA from the mother of the fetus (such as a mixed sample of cell-free DNA or RNA originating from a blood sample from the mother that includes fetal cell-free DNA or RNA and maternal cell-free DNA or RNA). In some embodiments, allele ratios are calculated for the loci that are heterozygous in the fetus and/or heterozygous in the mother. In some embodiments, the calculated allele ratio for a particular locus is the measured quantity of one of the alleles divided by the total measured quantity of all the alleles for the locus. In some embodiments, the calculated allele ratio for a particular locus is the measured quantity of one of the alleles (such as the allele on the first homologous

chromosome segment) divided by the measured quantity of one or more other alleles (such as the allele on the second homologous chromosome segment) for the locus. In some embodiments, a set of one or more hypotheses specifying the number of copies of the chromosome or chromosome segment in the genome of fetus are enumerated. In some embodiments, the hypothesis that is most likely based on the test statistic is selected, thereby determining the number of copies of the chromosome or chromosome segment in the genome of the fetus.

[0033] In some embodiments, a hypothesis is selected if the probability that the test statistic belongs to a distribution of the test statistic for that hypothesis is above an upper threshold; one or more of the hypotheses is rejected if the probability that the test statistic belongs to the distribution of the test statistic for that hypothesis is below a lower threshold; or a hypothesis is neither selected nor rejected if the probability that the test statistic belongs to the distribution of the test statistic for that hypothesis is between the lower threshold and the upper threshold, or if the probability is not determined with sufficiently high confidence.

[0034] In some embodiments, the overrepresentation of the number of copies of the first homologous chromosome segment is due to a duplication of the first homologous chromosome segment or a deletion of the second homologous chromosome segment. In some embodiments, the total measured quantity of all the alleles for one or more of the loci is compared to a reference amount to determine whether the overrepresentation of the number of copies of the first homologous chromosome segment is due to a duplication of the first homologous chromosome segment or a deletion of the second homologous chromosome segment. In some embodiments, the magnitude of the difference between the calculated allele ratio and the expected allele ratio for one or more loci is used to determine whether the overrepresentation of the number of copies of the first homologous chromosome segment is due to a duplication of the first homologous chromosome segment or a deletion of the second homologous chromosome segment. In some embodiments, the first and second homologous chromosome segments are determined to be present in equal proportions if there is not an overrepresentation of the number of copies of the first homologous chromosome segment, and there is not an overrepresentation of the second homologous chromosome segment (such as in the genome of the cells, cfDNA, cfRNA, individual, fetus, or embryo).

[0035] In some embodiments, the phased genetic data includes probabilistic data. In some embodiments, obtaining the phased genetic data for the first homologous chromosome segment and/or the second homologous chromosome segment in the genome of the fetus includes obtaining phased genetic data for the first homologous chromosome segment and/or the second homologous chromosome segment in the genome of one or both biological parents of the fetus, and inferring which homologous chromosome segment the fetus inherited from one or both biological parents. In some embodiments, the probability of one or more crossovers (such as 1, 2, 3, or 4 crossovers) that may have occurred during the formation of a gamete that contributed a copy of the first homologous chromosome segment or the second homologous chromosome segment to the fetus individual is used to infer which homologous chromosome segment(s) the fetus inherited from one or both biological parents. In some embodiments, phased genetic data for the mother and/or father of the fetus is obtained using a technique selected from the group consisting of digital PCR, inferring a haplotype using population based haplotype frequencies, haplotyping using a haploid cell such as a sperm or egg, haplotyping using genetic data from one or more first degree relatives, and combinations thereof.

[0036] In some embodiments, the method includes using a joint distribution model (such as a joint distribution model that takes into account the linkage between loci), performing a linkage analysis, using a binomial distribution model, using a beta-binomial distribution model, and/or using the likelihood of crossovers having occurred during the meiosis that gave rise to the gametes that formed the embryo that grew into the fetus (such as using the probability of chromosomes crossing over at different locations in a chromosome to model dependence between polymorphic alleles on the chromosome or chromosome segment of interest).

[0037] In some embodiments, one or more of the calculated allele ratios for the cfDNA or cfRNA are indicative of the corresponding allele ratios for DNA or RNA in the cells from which the cfDNA or cfRNA was derived. In some embodiments, one or more of the calculated allele ratios for the cfDNA or cfRNA are indicative of the corresponding allele ratios in the genome of the individual. In some embodiments, an allele ratio is only calculated or is only compared to an expected allele ratio if the measured genetic data indicate that more than one different allele is present for that locus in the sample (such as in a cfDNA or cfRNA sample). In some embodiments, an allele ratio is only calculated or is only compared to an expected allele ratio if the locus is heterozygous in at least one of the cells from which the sample was derived (such as

a locus that is heterozygous in the fetus and/or heterozygous in the mother). In some embodiments, an allele ratio is only calculated or is only compared to an expected allele ratio if the locus is heterozygous in the fetus. In some embodiments, an allele ratio is calculated and compared to an expected allele ratio for a homozygous locus. For example, allele ratios for loci that are predicted to be homozygous for a particular individual being tested (or for both a fetus and pregnant mother) may be analyzed to determine the level of noise or error in the system.

[0038] In some embodiments, at least 10; 50; 100; 200; 300; 500; 750; 1,000; 2,000; 3,000; 4,000, or more loci (such as SNPs) are analyzed for a chromosome or chromosome segment of interest. In some embodiments, the average number of loci (such as SNPs) per mb in a chromosome or chromosome segment of interest is at least 1; 10; 25; 50; 100; 150; 200; 300; 500; 750; 1,000; or more loci per mb. In some embodiments, the average number of loci (such as SNPs) per mb in a chromosome or chromosome segment of interest is between 1 and 500 loci per mb, such as between 1 and 50, 50 and 100, 100 and 200, 200 and 400, 200 and 300, or 300 and 400 loci per mb, inclusive. In some embodiments, only the two most common alleles at each locus are measured or are used to determine the calculated allele ratio. In some embodiments, the amplification of loci is performed using a polymerase (*e.g.*, a DNA polymerase, RNA polymerase, or reverse transcriptase) with low 5'→ 3' exonuclease and/or low strand displacement activity. In some embodiments, the measured genetic allelic data is obtained by (i) sequencing the DNA in the sample or (ii) amplifying DNA in the sample and then sequencing the amplified DNA. In some embodiments, measurements for different alleles for the same locus are adjusted for differences in metabolism, apoptosis, histones, inactivation, and/or amplification between the alleles (such as differences in amplification efficiency between different alleles of the same locus). In some embodiments, this adjustment is performed prior to calculating allele ratios for the obtained genetic data or prior to comparing the measured genetic data to the expected genetic data.

[0039] In some embodiments, the method also includes determining the presence or absence of one or more risk factors for a disease or disorder. In some embodiments, the method also includes determining the presence or absence of one or more polymorphisms or mutations associated with the disease or disorder or an increased risk for a disease or disorder. In some embodiments, the method also includes determining the total level of cfDNA cf mRNA, cf nDNA, cfRNA, miRNA, or any combination thereof. In some embodiments, the method

includes determining the level of one or more cfDNA cf mRNA, cf nDNA, cfRNA, and/or miRNA molecules of interest, such as molecules with a polymorphism or mutation associated with a disease or disorder or an increased risk for a disease or disorder. In some embodiments, the method also includes determining the total level of DNA or RNA level. In some embodiments, the method includes determining the methylation level of one or more DNA or RNA molecules of interest, such as molecules with a polymorphism or mutation associated with a disease or disorder or an increased risk for a disease or disorder. In some embodiments, the method includes determining the presence or absence of a change in DNA integrity. In some embodiments, the method also includes determining the total level of mRNA splicing. In some embodiments, the method includes determining the level of mRNA splicing or detecting alternative mRNA splicing for one or RNA molecules of interest, such as molecules with a polymorphism or mutation associated with a disease or disorder or an increased risk for a disease or disorder.

[0040] In some embodiments, the invention features a method for detecting a cancer phenotype in an individual, wherein the cancer phenotype is defined by the presence of at least one of a set of mutations. In some embodiments, the method includes obtaining DNA or RNA measurements for a sample of DNA or RNA from one or more cells from the individual, wherein one or more of the cells is suspected of having the cancer phenotype; and analyzing the DNA or RNA measurements to determine, for each of the mutations in the set of mutations, the likelihood that at least one of the cells has that mutation. In some embodiments, the method includes determining that the individual has the cancer phenotype if either (i) for at least one of the mutations, the likelihood that at least one of the cells contains that mutations is greater than a threshold, or (ii) for at least one of the mutations, the likelihood that at least one of the cells has that mutations is less than the threshold, and for a plurality of the mutations, the combined likelihood that at least one of the cells has at least one of the mutations is greater than the threshold. In some embodiments, one or more cells have a subset or all of the mutations in the set of mutations. In some embodiments, the subset of mutations is associated with cancer or an increased risk for cancer. In some embodiments, the sample includes cell-free DNA or RNA. In some embodiments, the DNA or RNA measurements include measurements (such as the quantity of each allele at each locus) at a set of polymorphic loci on one or more chromosomes or chromosome segments of interest.

[0041] In one aspect, the invention features methods for selecting a therapy for the treatment, stabilization, or prevention of a disease or disorder in a mammal. In some embodiments, the method includes determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment using any of the methods described herein. In some embodiments, a therapy is selected for the mammal (such as a therapy for a disease or disorder associated with the overrepresentation of the first homologous chromosome segment).

[0042] In one aspect, the invention features methods for preventing, delaying, stabilizing, or treating a disease or disorder in a mammal. In some embodiments, the method includes determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment using any of the methods described herein. In some embodiments, a therapy is selected for the mammal (such as a therapy for a disease or disorder associated with the overrepresentation of the first homologous chromosome segment) and then the therapy is administered to the mammal.

[0043] In some embodiments, treating, stabilizing, or preventing a disease or disorder includes preventing or delaying an initial or subsequent occurrence of a disease or disorder, increasing the disease-free survival time between the disappearance of a condition and its reoccurrence, stabilizing or reducing an adverse symptom associated with a condition, or inhibiting or stabilizing the progression of a condition. In some embodiments, at least 20, 40, 60, 80, 90, or 95% of the treated subjects have a complete remission in which all evidence of the condition disappears. In some embodiments, the length of time a subject survives after being diagnosed with a condition and treated is at least 20, 40, 60, 80, 100, 200, or even 500% greater than (i) the average amount of time an untreated subject survives or (ii) the average amount of time a subject treated with another therapy survives.

[0044] In some embodiments, treating, stabilizing, or preventing cancer includes reducing or stabilizing the size of a tumor (*e.g.*, a benign or malignant tumor), slowing or preventing an increase in the size of a tumor, reducing or stabilizing the number of tumor cells, increasing the disease-free survival time between the disappearance of a tumor and its reappearance, preventing an initial or subsequent occurrence of a tumor, or reducing or stabilizing an adverse symptom associated with a tumor. In one embodiment, the number of cancerous cells surviving the treatment is at least 10, 20, 40, 60, 80, or 100% lower than the initial number of cancerous cells,

as measured using any standard assay. In some embodiments, the decrease in the number of cancerous cells induced by administration of a therapy of the invention is at least 2, 5, 10, 20, or 50-fold greater than the decrease in the number of non-cancerous cells. In some embodiments, the number of cancerous cells present after administration of a therapy is at least 2, 5, 10, 20, or 50-fold lower than the number of cancerous cells present after administration of a control (such as administration of saline or a buffer). In some embodiments, the methods of the present invention result in a decrease of 10, 20, 40, 60, 80, or 100% in the size of a tumor as determined using standard methods. In some embodiments, at least 10, 20, 40, 60, 80, 90, or 95% of the treated subjects have a complete remission in which there are no detectable cancerous cells. In some embodiments, the cancer does not reappear, or reappears after at least 2, 5, 10, 15, or 20 years. In some embodiments, the length of time a subject survives after being diagnosed with cancer and treated with a therapy of the invention is at least 10, 20, 40, 60, 80, 100, 200, or even 500% greater than (i) the average amount of time an untreated subject survives or (ii) the average amount of time a subject treated with another therapy survives.

[0045] In one aspect, the invention features methods for stratification of subjects involved in a clinical trial for the treatment, stabilization, or prevention of a disease or disorder in a mammal. In some embodiments, the method includes determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment using any of the methods described herein before, during, or after the clinical trial. In some embodiments, the presence or absence of the overrepresentation of the first homologous chromosome segment in the genome of the subject places the subject into a subgroup for the clinical trial.

[0046] In some embodiments, the disease or disorder is selected from the group consisting of cancer, mental handicap, learning disability (*e.g.*, idiopathic learning disability), mental retardation, developmental delay, autism, neurodegenerative disease or disorder, schizophrenia, physical handicap, autoimmune disease or disorder, systemic lupus erythematosus, psoriasis, Crohn's disease, glomerulonephritis, HIV infection, AIDS, and combinations thereof. In some embodiments, the disease or disorder is selected from the group consisting of DiGeorge syndrome, DiGeorge 2 syndrome, DiGeorge/VCFS syndrome, Prader-Willi syndrome, Angelman syndrome, Beckwith-Wiedemann syndrome, 1p36 deletion syndrome, 2q37 deletion syndrome, 3q29 deletion syndrome, 9q34 deletion syndrome, 17q21.31 deletion syndrome, Cri-

du-chat syndrome, Jacobsen syndrome, Miller Dieker syndrome, Phelan-McDermid syndrome, Smith-Magenis syndrome, WAGR syndrome, Wolf-Hirschhorn syndrome, Williams syndrome, Williams-Beuren syndrome, Miller-Dieker syndrome, Phelan-McDermid syndrome, Smith-Magenis syndrome, Down syndrome, Edward syndrome, Patau syndrome, Klinefelter syndrome, Turner syndrome, 47,XXX syndrome, 47,XYY syndrome, Sotos syndrome, and combinations thereof. In some embodiments, the method determines the presence or absence of one or more of the following chromosomal abnormalities: nullsomy, monosomy, uniparental disomy, trisomy, matched trisomy, unmatched trisomy, maternal trisomy, paternal trisomy, triploidy, mosaicism tetrasomy, matched tetrasomy, unmatched tetrasomy, other aneuploidies, unbalanced translocations, balanced translocations, insertions, deletions, recombinations, and combinations thereof. In some embodiments, the method determines the presence or absence of a euploidy. In some embodiments, the chromosome segment of interest is an entire chromosome. In some embodiments, the chromosome or chromosome segment is selected from the group consisting of chromosome 13, chromosome 18, chromosome 21, the X chromosome, the Y chromosome, segments thereof, and combinations thereof. In some embodiments, the first homologous chromosome segment and second homologous chromosome segment are a pair of homologous chromosome segments that comprises the chromosome segment of interest. In some embodiments, the first homologous chromosome segment and second homologous chromosome segment are a pair of homologous chromosomes of interest. In some embodiments, a confidence is computed for the CNV determination or the diagnosis of the disease or disorder.

[0047] In some embodiments, the deletion is a deletion of at least 0.01 kb, 0.1 kb, 1 kb, 10 kb, 100 kb, 1 mb, 2 mb, 3 mb, 5 mb, 10 mb, 15 mb, 20 mb, 30 mb, or 40 mb. In some embodiments, the deletion is a deletion of between 1 kb to 40 mb, such as between 1 kb to 100 kb, 100 kb to 1 mb, 1 to 5 mb, 5 to 10 mb, 10 to 15 mb, 15 to 20 mb, 20 to 25 mb, 25 to 30 mb, or 30 to 40 mb, inclusive. In some embodiments, one copy of the chromosome segment is deleted and one copy is present. In some embodiments, two copies of the chromosome segment are deleted. In some embodiments, an entire chromosome is deleted.

[0048] In some embodiments, the duplication is a duplication of at least 0.01 kb, 0.1 kb, 1 kb, 10 kb, 100 kb, 1 mb, 2 mb, 3 mb, 5 mb, 10 mb, 15 mb, 20 mb, 30 mb, or 40 mb. In some embodiments, the duplication is a duplication of between 1 kb to 40 mb, such as between 1 kb to 100 kb, 100 kb to 1 mb, 1 to 5 mb, 5 to 10 mb, 10 to 15 mb, 15 to 20 mb, 20 to 25 mb, 25 to 30

mb, or 30 to 40 mb, inclusive. In some embodiments, the chromosome segment is duplicated one time. In some embodiments, the chromosome segment is duplicated more than one time, such as 2, 3, 4, or 5 times. In some embodiments, an entire chromosome is duplicated. In some embodiments, a region in a first homologous segment is deleted, and the same region or another region in the second homologous segment is duplicated.

[0049] In some embodiments, the sample comprises DNA and/or RNA from (i) one or more target cells or (ii) one or more non-target cells. In some embodiments, the sample is a mixed sample with DNA and/or RNA from one or more target cells and one or more non-target cells. In some embodiments, the target cells are cells that have a CNV, such as a deletion or duplication of interest, and the non-target cells are cells that do not have the copy number variation of interest. In some embodiments in which the one or more target cells are cancer cell(s) and the one or more non-target cells are non-cancerous cell(s), the method includes determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment in the genome of one or more of the cancer cells. In some embodiments in which the one or more target cells are genetically identical cancer cell(s) and the one or more non-target cells are non-cancerous cell(s), the method includes determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment in the genome of the cancer cell(s). In some embodiments in which the one or more target cells are genetically non-identical cancer cell(s) and the one or more non-target cells are non-cancerous cell(s), the method includes determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment in the genome of one or more of the genetically non-identical cancer cells. In some embodiments in which the sample comprises cell-free DNA from a mixture of one or more cancer cells and one or more non-cancerous cells, the method includes determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment in the genome of one or more of the cancer cells. In some embodiments in which the one or more target cells are genetically identical fetal cell(s) and the one or more non-target cells are maternal cell(s), the method includes determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment in the genome of the fetal cell(s). In some embodiments in which the one or more target cells are genetically non-identical fetal cell(s) and the one or more non-target cells are maternal cell(s), the method includes determining if there is an overrepresentation of the number of copies of the

first homologous chromosome segment in the genome of one or more of the genetically non-identical fetal cells.

[0050] In some embodiments, the sample is obtained from a maternal whole blood sample or fraction thereof, cells isolated from a maternal blood sample, an amniocentesis sample, a products of conception sample, a placental tissue sample, a chorionic villus sample, a placental membrane sample, a cervical mucus sample, or a sample from a fetus. In some embodiments, the sample comprises cell-free DNA obtained from a blood sample or fraction thereof from the mother. In some embodiments, the sample comprises nuclear DNA obtained from a mixture of fetal cells and maternal cells. In some embodiments, the sample is obtained from a fraction of maternal blood containing nucleated cells that has been enriched for fetal cells. In some embodiments, a sample is divided into multiple fractions (such as 2, 3, 4, 5, or more fractions) that are each analyzed using a method of the invention. If each fraction produces the same results (such as the presence or absence of one or more CNVs of interest), the confidence in the results increases. In different fractions produce different results, the sample could be re-analyzed or another sample could be collected from the same subject and analyzed.

[0051] Exemplary subjects include mammals, such as humans and mammals of veterinary interest. In some embodiments, the mammal is a primate (*e.g.*, a human, a monkey, a gorilla, an ape, a lemur, *etc.*), a bovine, an equine, a porcine, a canine, or a feline.

[0052] In some embodiments, any of the methods include generating a report (such as a written or electronic report) disclosing a result of the method of the invention (such as the presence or absence of a deletion or duplication).

[0053] In one aspect, the invention features a report (such as a written or electronic report) with a result from a method of the invention (such as the presence or absence of a deletion or duplication).

[0054] In various embodiments, the primer extension reaction or the polymerase chain reaction includes the addition of one or more nucleotides by a polymerase. In some embodiments, the primers are in solution. In some embodiments, the primers are in solution and are not immobilized on a solid support. In some embodiments, the primers are not part of a microarray. In various embodiments, the primer extension reaction or the polymerase chain reaction does not include ligation-mediated PCR. In various embodiments, the primer extension reaction or the polymerase chain reaction does not include the joining of two primers by a ligase. In various

embodiments, the primers do not include Linked Inverted Probes (LIPs), which can also be called pre-circularized probes, pre-circularizing probes, circularizing probes, Padlock Probes, or Molecular Inversion Probes (MIPs).

[0055] It is understood that aspects and embodiments of the invention described herein include “comprising,” “consisting,” and “consisting essentially of” aspects and embodiments. It is understood that aspects and embodiments of the invention described herein include combinations of any two or more of the aspects or embodiments of the invention.

Definitions

[0056] *Single Nucleotide Polymorphism (SNP)* refers to a single nucleotide that may differ between the genomes of two members of the same species. The usage of the term should not imply any limit on the frequency with which each variant occurs.

[0057] *Sequence* refers to a DNA sequence or a genetic sequence. It may refer to the primary, physical structure of the DNA molecule or strand in an individual. It may refer to the sequence of nucleotides found in that DNA molecule, or the complementary strand to the DNA molecule. It may refer to the information contained in the DNA molecule as its representation *in silico*.

[0058] *Locus* refers to a particular region of interest on the DNA of an individual, which may refer to a SNP, the site of a possible insertion or deletion, or the site of some other relevant genetic variation. Disease-linked SNPs may also refer to disease-linked loci.

[0059] *Polymorphic Allele*, also “*Polymorphic Locus*,” refers to an allele or locus where the genotype varies between individuals within a given species. Some examples of polymorphic alleles include single nucleotide polymorphisms, short tandem repeats, deletions, duplications, and inversions.

[0060] *Polymorphic Site* refers to the specific nucleotides found in a polymorphic region that vary between individuals.

[0061] *Mutation* refers to an alteration in a naturally-occurring or reference nucleic acid sequence, such as an insertion, deletion, duplication, translocation, substitution, frameshift mutation, silent mutation, nonsense mutation, missense mutation, point mutation, transition mutation, transversion mutation, reverse mutation, or microsatellite alteration. In some embodiments, the amino acid sequence encoded by the nucleic acid sequence has at least one amino acid alteration from a naturally-occurring sequence.

[0062] *Allele* refers to the genes that occupy a particular locus.

[0063] *Genetic Data* also “*Genotypic Data*” refers to the data describing aspects of the genome of one or more individuals. It may refer to one or a set of loci, partial or entire sequences, partial or entire chromosomes, or the entire genome. It may refer to the identity of one or a plurality of nucleotides; it may refer to a set of sequential nucleotides, or nucleotides from different locations in the genome, or a combination thereof. Genotypic data is typically *in silico*, however, it is also possible to consider physical nucleotides in a sequence as chemically encoded genetic data. Genotypic Data may be said to be “on,” “of,” “at,” “from” or “on” the individual(s). Genotypic Data may refer to output measurements from a genotyping platform where those measurements are made on genetic material.

[0064] *Genetic Material* also “*Genetic Sample*” refers to physical matter, such as tissue or blood, from one or more individuals comprising DNA or RNA.

[0065] *Confidence* refers to the statistical likelihood that the called SNP, allele, set of alleles, determined number of copies of a chromosome or chromosome segment, or diagnosis of the presence or absence of a disease correctly represents the real genetic state of the individual.

[0066] *Ploidy Calling*, also “Chromosome Copy Number Calling,” or “Copy Number Calling” (CNC), may refer to the act of determining the quantity and/or chromosomal identity of one or more chromosomes or chromosome segments present in a cell.

[0067] *Aneuploidy* refers to the state where the wrong number of chromosomes (*e.g.*, the wrong number of full chromosomes or the wrong number of chromosome segments, such as the presence of deletions or duplications of a chromosome segment) is present in a cell. In the case of a somatic human cell it may refer to the case where a cell does not contain 22 pairs of autosomal chromosomes and one pair of sex chromosomes. In the case of a human gamete, it may refer to the case where a cell does not contain one of each of the 23 chromosomes. In the case of a single chromosome type, it may refer to the case where more or less than two homologous but non-identical chromosome copies are present, or where there are two chromosome copies present that originate from the same parent. In some embodiments, the deletion of a chromosome segment is a microdeletion.

[0068] *Ploidy State* refers to the quantity and/or chromosomal identity of one or more chromosomes or chromosome segments in a cell.

[0069] *Chromosome* may refer to a single chromosome copy, meaning a single molecule of DNA of which there are 46 in a normal somatic cell; an example is ‘the maternally derived chromosome 18’. Chromosome may also refer to a chromosome type, of which there are 23 in a normal human somatic cell; an example is ‘chromosome 18’.

[0070] *Chromosomal Identity* may refer to the referent chromosome number, *i.e.* the chromosome type. Normal humans have 22 types of numbered autosomal chromosome types, and two types of sex chromosomes. It may also refer to the parental origin of the chromosome. It may also refer to a specific chromosome inherited from the parent. It may also refer to other identifying features of a chromosome.

[0071] *Allelic Data* refers to a set of genotypic data concerning a set of one or more alleles. It may refer to the phased, haplotypic data. It may refer to SNP identities, and it may refer to the sequence data of the DNA, including insertions, deletions, repeats and mutations. It may include the parental origin of each allele.

[0072] *Allelic State* refers to the actual state of the genes in a set of one or more alleles. It may refer to the actual state of the genes described by the allelic data.

[0073] *Allele Count* refers to the number of sequences that map to a particular locus, and if that locus is polymorphic, it refers to the number of sequences that map to each of the alleles. If each allele is counted in a binary fashion, then the allele count will be whole number. If the alleles are counted probabilistically, then the allele count can be a fractional number.

[0074] *Allele Count Probability* refers to the number of sequences that are likely to map to a particular locus or a set of alleles at a polymorphic locus, combined with the probability of the mapping. Note that allele counts are equivalent to allele count probabilities where the probability of the mapping for each counted sequence is binary (zero or one). In some embodiments, the allele count probabilities may be binary. In some embodiments, the allele count probabilities may be set to be equal to the DNA measurements.

[0075] *Allelic Distribution*, or “*allele count distribution*” refers to the relative amount of each allele that is present for each locus in a set of loci. An allelic distribution can refer to an individual, to a sample, or to a set of measurements made on a sample. In the context of digital allele measurements such as sequencing, the allelic distribution refers to the number or probable number of reads that map to a particular allele for each allele in a set of polymorphic loci. In the context of analog allele measurements such as SNP arrays, the allelic distribution refers to allele

intensities and/or allele ratios. The allele measurements may be treated probabilistically, that is, the likelihood that a given allele is present for a give sequence read is a fraction between 0 and 1, or they may be treated in a binary fashion, that is, any given read is considered to be exactly zero or one copies of a particular allele.

[0076] *Allelic Distribution Pattern* refers to a set of different allele distributions for different contexts, such as different parental contexts. Certain allelic distribution patterns may be indicative of certain ploidy states.

[0077] *Allelic Bias* refers to the degree to which the measured ratio of alleles at a heterozygous locus is different to the ratio that was present in the original sample of DNA or RNA. The degree of allelic bias at a particular locus is equal to the observed allelic ratio at that locus, as measured, divided by the ratio of alleles in the original DNA or RNA sample at that locus. Allelic bias maybe due to amplification bias, purification bias, or some other phenomenon that affects different alleles differently.

[0078] *Primer*, also “*PCR probe*” refers to a single nucleic acid molecule (such as a DNA molecule or a DNA oligomer) or a collection of nucleic acid molecules (such as DNA molecules or DNA oligomers) where the molecules are identical, or nearly so, and wherein the primer contains a region that is designed to hybridize to a targeted locus (*e.g.*, a targeted polymorphic locus or a non-polymorphic locus) or to a universal priming sequence, and may contain a priming sequence designed to allow PCR amplification. A primer may also contain a molecular barcode. A primer may contain a random region that differs for each individual molecule.

[0079] *Library of primers* refers to a population of two or more primers. In various embodiments, the library includes at least 100; 200; 500; 750; 1,000; 2,000; 5,000; 7,500; 10,000; 20,000; 25,000; 30,000; 40,000; 50,000; 75,000; or 100,000 different primers. In various embodiments, the library includes at least 100; 200; 500; 750; 1,000; 2,000; 5,000; 7,500; 10,000; 20,000; 25,000; 30,000; 40,000; 50,000; 75,000; or 100,000 different primer pairs, wherein each pair of primers includes a forward test primer and a reverse test primer where each pair of test primers hybridize to a target locus. In some embodiments, the library of primers includes at least 100; 200; 500; 750; 1,000; 2,000; 5,000; 7,500; 10,000; 20,000; 25,000; 30,000; 40,000; 50,000; 75,000; or 100,000 different individual primers that each hybridize to a different target locus, wherein the individual primers are not part of primer pairs. In some embodiments,

the library has both (i) primer pairs and (ii) individual primers (such as universal primers) that are not part of primer pairs.

[0080] *Hybrid Capture Probe* refers to any nucleic acid sequence, possibly modified, that is generated by various methods such as PCR or direct synthesis and intended to be complementary to one strand of a specific target DNA sequence in a sample. The exogenous hybrid capture probes may be added to a prepared sample and hybridized through a denature-reannealing process to form duplexes of exogenous-endogenous fragments. These duplexes may then be physically separated from the sample by various means.

[0081] *Sequence Read* refers to data representing a sequence of nucleotide bases that were measured, *e.g.*, using a clonal sequencing method. Clonal sequencing may produce sequence data representing single, or clones, or clusters of one original DNA molecule. A sequence read may also have associated quality score at each base position of the sequence indicating the probability that nucleotide has been called correctly.

[0082] *Mapping a sequence read* is the process of determining a sequence read's location of origin in the genome sequence of a particular organism. The location of origin of sequence reads is based on similarity of nucleotide sequence of the read and the genome sequence.

[0083] *Matched Copy Error*, also “*Matching Chromosome Aneuploidy*” (MCA), refers to a state of aneuploidy where one cell contains two identical or nearly identical chromosomes. This type of aneuploidy may arise during the formation of the gametes in meiosis, and may be referred to as a meiotic non-disjunction error. This type of error may arise in mitosis. Matching trisomy may refer to the case where three copies of a given chromosome are present in an individual and two of the copies are identical.

[0084] *Unmatched Copy Error*, also “*Unique Chromosome Aneuploidy*” (UCA), refers to a state of aneuploidy where one cell contains two chromosomes that are from the same parent, and that may be homologous but not identical. This type of aneuploidy may arise during meiosis, and may be referred to as a meiotic error. Unmatching trisomy may refer to the case where three copies of a given chromosome are present in an individual and two of the copies are from the same parent, and are homologous, but are not identical. Note that unmatching trisomy may refer to the case where two homologous chromosomes from one parent are present, and where some segments of the chromosomes are identical while other segments are merely homologous.

[0085] *Homologous Chromosomes* refers to chromosome copies that contain the same set of genes that normally pair up during meiosis.

[0086] *Identical Chromosomes* refers to chromosome copies that contain the same set of genes, and for each gene they have the same set of alleles that are identical, or nearly identical.

[0087] *Allele Drop Out (ADO)* refers to the situation where at least one of the base pairs in a set of base pairs from homologous chromosomes at a given allele is not detected.

[0088] *Locus Drop Out (LDO)* refers to the situation where both base pairs in a set of base pairs from homologous chromosomes at a given allele are not detected.

[0089] *Homozygous* refers to having similar alleles as corresponding chromosomal loci.

[0090] *Heterozygous* refers to having dissimilar alleles as corresponding chromosomal loci.

[0091] *Heterozygosity Rate* refers to the rate of individuals in the population having heterozygous alleles at a given locus. The heterozygosity rate may also refer to the expected or measured ratio of alleles, at a given locus in an individual, or a sample of DNA or RNA.

[0092] *Chromosomal Region* refers to a segment of a chromosome, or a full chromosome.

[0093] *Segment of a Chromosome* refers to a section of a chromosome that can range in size from one base pair to the entire chromosome.

[0094] *Chromosome* refers to either a full chromosome, or a segment or section of a chromosome.

[0095] *Copies* refers to the number of copies of a chromosome segment. It may refer to identical copies, or to non-identical, homologous copies of a chromosome segment wherein the different copies of the chromosome segment contain a substantially similar set of loci, and where one or more of the alleles are different. Note that in some cases of aneuploidy, such as the M2 copy error, it is possible to have some copies of the given chromosome segment that are identical as well as some copies of the same chromosome segment that are not identical.

[0096] *Haplotype* refers to a combination of alleles at multiple loci that are typically inherited together on the same chromosome. Haplotype may refer to as few as two loci or to an entire chromosome depending on the number of recombination events that have occurred between a given set of loci. Haplotype can also refer to a set of SNPs on a single chromatid that are statistically associated.

[0097] *Haplotypic Data*, also “*Phased Data*” or “*Ordered Genetic Data*,” refers to data from a single chromosome or chromosome segment in a diploid or polyploid genome, *e.g.*, either the segregated maternal or paternal copy of a chromosome in a diploid genome.

[0098] *Phasing* refers to the act of determining the haplotypic genetic data of an individual given unordered, diploid (or polyploidy) genetic data. It may refer to the act of determining which of two genes at an allele, for a set of alleles found on one chromosome, are associated with each of the two homologous chromosomes in an individual.

[0099] *Phased Data* refers to genetic data where one or more haplotypes have been determined.

[00100] *Hypothesis* refers to a possible state, such as a possible degree of overrepresentation of the number of copies of a first homologous chromosome or chromosome segment as compared to a second homologous chromosome or chromosome segment, a possible deletion, a possible duplication, a possible ploidy state at a given set of one or more chromosomes or chromosome segments, a possible allelic state at a given set of one or more loci, a possible paternity relationship, or a possible DNA, RNA, or fetal fraction at a given set of one or more chromosomes or chromosome segment. The set of possibilities may comprise one or more elements.

[00101] *Copy Number Hypothesis*, also “*Ploidy State Hypothesis*,” refers to a hypothesis concerning the number of copies of a chromosome or chromosome segment in an individual. It may also refer to a hypothesis concerning the identity of each of the chromosomes, including the parent of origin of each chromosome, and which of the parent’s two chromosomes are present in the individual. It may also refer to a hypothesis concerning which chromosomes, or chromosome segments, if any, from a related individual correspond genetically to a given chromosome from an individual.

[00102] *Related Individual* refers to any individual who is genetically related to, and thus shares haplotype blocks with, the target individual. In one context, the related individual may be a genetic parent of the target individual, or any genetic material derived from a parent, such as a sperm, a polar body, an embryo, a fetus, or a child. It may also refer to a sibling, parent, or grandparent.

[00103] *Sibling* refers to any individual whose genetic parents are the same as the individual in question. In some embodiments, it may refer to a born child, an embryo, or a fetus, or one or more cells originating from a born child, an embryo, or a fetus. A sibling may also refer to a

haploid individual that originates from one of the parents, such as a sperm, a polar body, or any other set of haplotypic genetic matter. An individual may be considered to be a sibling of itself.

[00104] *Child* may refer to an embryo, a blastomere, or a fetus. Note that in the presently disclosed embodiments, the concepts described apply equally well to individuals who are a born child, a fetus, an embryo, or a set of cells therefrom. The use of the term child may simply be meant to connote that the individual referred to as the child is the genetic offspring of the parents.

[00105] *Fetal* refers to “of the fetus,” or “of the region of the placenta that is genetically similar to the fetus”. In a pregnant woman, some portion of the placenta is genetically similar to the fetus, and the free floating fetal DNA found in maternal blood may have originated from the portion of the placenta with a genotype that matches the fetus. Note that the genetic information in half of the chromosomes in a fetus is inherited from the mother of the fetus. In some embodiments, the DNA from these maternally inherited chromosomes that came from a fetal cell is considered to be “of fetal origin,” not “of maternal origin.”

[00106] *DNA of Fetal Origin* refers to DNA that was originally part of a cell whose genotype was essentially equivalent to that of the fetus.

[00107] *DNA of Maternal Origin* refers to DNA that was originally part of a cell whose genotype was essentially equivalent to that of the mother.

[00108] *Parent* refers to the genetic mother or father of an individual. An individual typically has two parents, a mother and a father, though this may not necessarily be the case such as in genetic or chromosomal chimerism. A parent may be considered to be an individual.

[00109] *Parental Context* refers to the genetic state of a given SNP, on each of the two relevant chromosomes for one or both of the two parents of the target.

[00110] *Maternal Plasma* refers to the plasma portion of the blood from a female who is pregnant.

[00111] *Clinical Decision* refers to any decision to take or not take an action that has an outcome that affects the health or survival of an individual. A clinical decision may also refer to a decision to conduct further testing, to take actions to mitigate an undesirable phenotype, or to take actions to prepare for a phenotype.

[00112] *Diagnostic Box* refers to one or a combination of machines designed to perform one or a plurality of aspects of the methods disclosed herein. In an embodiment, the diagnostic box may

be placed at a point of patient care. In an embodiment, the diagnostic box may perform targeted amplification followed by sequencing. In an embodiment the diagnostic box may function alone or with the help of a technician.

[00113] *Informatics Based Method* refers to a method that relies heavily on statistics to make sense of a large amount of data. In the context of prenatal diagnosis, it refers to a method designed to determine the ploidy state at one or more chromosomes or chromosome segments, the allelic state at one or more alleles, or paternity by statistically inferring the most likely state, rather than by directly physically measuring the state, given a large amount of genetic data, for example from a molecular array or sequencing. In an embodiment of the present disclosure, the informatics based technique may be one disclosed in this patent application. In an embodiment of the present disclosure it may be PARENTAL SUPPORT.

[00114] *Primary Genetic Data* refers to the analog intensity signals that are output by a genotyping platform. In the context of SNP arrays, primary genetic data refers to the intensity signals before any genotype calling has been done. In the context of sequencing, primary genetic data refers to the analog measurements, analogous to the chromatogram, that comes off the sequencer before the identity of any base pairs have been determined, and before the sequence has been mapped to the genome.

[00115] *Secondary Genetic Data* refers to processed genetic data that are output by a genotyping platform. In the context of a SNP array, the secondary genetic data refers to the allele calls made by software associated with the SNP array reader, wherein the software has made a call whether a given allele is present or not present in the sample. In the context of sequencing, the secondary genetic data refers to the base pair identities of the sequences have been determined, and possibly also where the sequences have been mapped to the genome.

[00116] *Preferential Enrichment* of DNA that corresponds to a locus, or preferential enrichment of DNA at a locus, refers to any method that results in the percentage of molecules of DNA in a post-enrichment DNA mixture that correspond to the locus being higher than the percentage of molecules of DNA in the pre-enrichment DNA mixture that correspond to the locus. The method may involve selective amplification of DNA molecules that correspond to a locus. The method may involve removing DNA molecules that do not correspond to the locus. The method may involve a combination of methods. The degree of enrichment is defined as the percentage of molecules of DNA in the post-enrichment mixture that correspond to the locus divided by the

percentage of molecules of DNA in the pre-enrichment mixture that correspond to the locus. Preferential enrichment may be carried out at a plurality of loci. In some embodiments of the present disclosure, the degree of enrichment is greater than 20, 200, or 2,000. When preferential enrichment is carried out at a plurality of loci, the degree of enrichment may refer to the average degree of enrichment of all of the loci in the set of loci.

[00117] *Amplification* refers to a method that increases the number of copies of a molecule of DNA or RNA.

[00118] *Selective Amplification* may refer to a method that increases the number of copies of a particular molecule of DNA (or RNA), or molecules of DNA (or RNA) that correspond to a particular region of DNA (or RNA). It may also refer to a method that increases the number of copies of a particular targeted molecule of DNA (or RNA), or targeted region of DNA (or RNA) more than it increases non-targeted molecules or regions of DNA (or RNA). Selective amplification may be a method of preferential enrichment.

[00119] *Universal Priming Sequence* refers to a DNA (or RNA) sequence that may be appended to a population of target DNA (or RNA) molecules, for example by ligation, PCR, or ligation mediated PCR. Once added to the population of target molecules, primers specific to the universal priming sequences can be used to amplify the target population using a single pair of amplification primers. Universal priming sequences are typically not related to the target sequences.

[00120] *Universal Adapters*, or “*ligation adaptors*” or “*library tags*” are nucleic acid molecules containing a universal priming sequence that can be covalently linked to the 5-prime and 3-prime end of a population of target double stranded nucleic acid molecules. The addition of the adapters provides universal priming sequences to the 5-prime and 3-prime end of the target population from which PCR amplification can take place, amplifying all molecules from the target population, using a single pair of amplification primers.

[00121] *Targeting* refers to a method used to selectively amplify or otherwise preferentially enrich those molecules of DNA (or RNA) that correspond to a set of loci in a mixture of DNA (or RNA).

[00122] *Joint Distribution Model* refers to a model that defines the probability of events defined in terms of multiple random variables, given a plurality of random variables defined on the same

probability space, where the probabilities of the variable are linked. In some embodiments, the degenerate case where the probabilities of the variables are not linked may be used.

[00123] *Cancer-related gene* refers to a gene associated with an altered risk for a cancer or an altered prognosis for a cancer. Exemplary cancer-related genes that promote cancer include oncogenes; genes that enhance cell proliferation, invasion, or metastasis; genes that inhibit apoptosis; and pro-angiogenesis genes. Cancer-related genes that inhibit cancer include, but are not limited to, tumor suppressor genes; genes that inhibit cell proliferation, invasion, or metastasis; genes that promote apoptosis; and anti-angiogenesis genes.

[00124] *Estrogen-related cancer* refers to a cancer that is modulated by estrogen. Examples of estrogen-related cancers include, without limitation, breast cancer and ovarian cancer. Her2 is overexpressed in many estrogen-related cancers (U.S. Pat. No. 6,165,464, which is hereby incorporated by reference in its entirety).

[00125] *Androgen-related cancer* refers to a cancer that is modulated by androgen. An example of androgen-related cancers is prostate cancer.

[00126] *Higher than normal expression level* refers to expression of an mRNA or protein at a level that is higher than the average expression level of the corresponding molecule in control subjects (such as subjects without a disease or disorder such as cancer). In various embodiments, the expression level is at least 20, 40, 50, 75, 90, 100, 200, 500, or even 1000% higher than the level in control subjects.

[00127] *Lower than normal expression level* refers to expression of an mRNA or protein at a level that is lower than the average expression level of the corresponding molecule in control subjects (such as subjects without a disease or disorder such as cancer). In various embodiments, the expression level is at least 20, 40, 50, 75, 90, 95, or 100% lower than the level in control subjects. In some embodiments, the expression of the mRNA or protein is not detectable.

[00128] *Modulate expression or activity* refers to either increasing or decreasing expression or activity, for example, of a protein or nucleic acid sequence, relative to control conditions. In some embodiments, the modulation in expression or activity is an increase or decrease of at least 10, 20, 40, 50, 75, 90, 100, 200, 500, or even 1000%. In various embodiments, transcription, translation, mRNA or protein stability, or the binding of the mRNA or protein to other molecules *in vivo* is modulated by the therapy. In some embodiments, the level of mRNA is determined by standard Northern blot analysis, and the level of protein is determined by standard Western blot

analysis, such as the analyses described herein or those described by, for example, Ausubel *et al.* (Current Protocols in Molecular Biology, John Wiley & Sons, New York, July 11, 2013, which is hereby incorporated by reference in its entirety). In one embodiment, the level of a protein is determined by measuring the level of enzymatic activity, using standard methods. In another preferred embodiment, the level of mRNA, protein, or enzymatic activity is equal to or less than 20, 10, 5, or 2-fold above the corresponding level in control cells that do not express a functional form of the protein, such as cells homozygous for a nonsense mutation. In yet another embodiment, the level of mRNA, protein, or enzymatic activity is equal to or less than 20, 10, 5, or 2-fold above the corresponding basal level in control cells, such as non-cancerous cells, cells that have not been exposed to conditions that induce abnormal cell proliferation or that inhibit apoptosis, or cells from a subject without the disease or disorder of interest.

[00129] *Dosage sufficient to modulate mRNA or protein expression or activity* refers to an amount of a therapy that increases or decreases mRNA or protein expression or activity when administered to a subject. In some embodiments, for a compound that decreases expression or activity, the modulation is a decrease in expression or activity that is at least 10%, 30%, 40%, 50%, 75%, or 90% lower in a treated subject than in the same subject prior to the administration of the inhibitor or than in an untreated, control subject. In addition, In some embodiments, for a compound that increases expression or activity, the amount of expression or activity of the mRNA or protein is at least 1.5-, 2-, 3-, 5-, 10-, or 20-fold greater in a treated subject than in the same subject prior to the administration of the modulator or than in an untreated, control subject.

[00130] In some embodiments, compounds may directly or indirectly modulate the expression or activity of the mRNA or protein. For example, a compound may indirectly modulate the expression or activity of an mRNA or protein of interest by modulating the expression or activity of a molecule (*e.g.*, a nucleic acid, protein, signaling molecule, growth factor, cytokine, or chemokine) that directly or indirectly affects the expression or activity of the mRNA or protein of interest. In some embodiments, the compounds inhibit cell division or induce apoptosis. These compounds in the therapy may include, for example, unpurified or purified proteins, antibodies, synthetic organic molecules, naturally-occurring organic molecules, nucleic acid molecules, and components thereof. The compounds in a combination therapy may be administered simultaneously or sequentially. Exemplary compounds include signal transduction inhibitors.

[00131] *Purified* refers to being separated from other components that naturally accompany it. Typically, a factor is substantially pure when it is at least 50%, by weight, free from proteins, antibodies, and naturally-occurring organic molecules with which it is naturally associated. In some embodiments, the factor is at least 75%, 90%, or 99%, by weight, pure. A substantially pure factor may be obtained by chemical synthesis, separation of the factor from natural sources, or production of the factor in a recombinant host cell that does not naturally produce the factor. Proteins and small molecules may be purified by one skilled in the art using standard techniques such as those described by Ausubel *et al.* (Current Protocols in Molecular Biology, John Wiley & Sons, New York, July 11, 2013, which is hereby incorporated by reference in its entirety). In some embodiments the factor is at least 2, 5, or 10 times as pure as the starting material, as measured using polyacrylamide gel electrophoresis, column chromatography, optical density, HPLC analysis, or western analysis (Ausubel *et al.*, *supra*). Exemplary methods of purification include immunoprecipitation, column chromatography such as immunoaffinity chromatography, magnetic bead immunoaffinity purification, and panning with a plate-bound antibody.

[00132] Other features and advantages of the invention will be apparent from the following detailed description and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[00133] The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

[00134] The presently disclosed embodiments will be further explained with reference to the attached drawings, wherein like structures are referred to by like numerals throughout the several views. The drawings shown are not necessarily to scale, with emphasis instead generally being placed upon illustrating the principles of the presently disclosed embodiments.

[00135] FIGs. 1A-1D are graphs showing the distribution of the test statistic S divided by T (the number of SNPs) (" S/T ") for various copy number hypotheses for a depth of read (DOR) of 500 and a tumor fraction of 1% for an increasing number of SNPs.

[00136] FIGs. 2A-2D are graphs showing the distribution of S/T for various copy number hypotheses for a DOR of 500 and tumor fraction of 2% for an increasing number of SNPs.

[00137] FIGs. 3A-3D are graphs showing the distribution of S/T for various copy number hypotheses for a DOR of 500 and tumor fraction of 3% for an increasing number of SNPs.

[00138] FIGs. 4A-4D are graphs showing the distribution of S/T for various copy number hypotheses for a DOR of 500 and tumor fraction of 4% for an increasing number of SNPs.

[00139] FIGs. 5A-5D are graphs showing the distribution of S/T for various copy number hypotheses for a DOR of 500 and tumor fraction of 5% for an increasing number of SNPs.

[00140] FIGs. 6A-6D are graphs showing the distribution of S/T for various copy number hypotheses for a DOR of 500 and tumor fraction of 6% for an increasing number of SNPs.

[00141] FIGs. 7A-7D are graphs showing the distribution of S/T for various copy number hypotheses for a DOR of 1000 and tumor fraction of 0.5% for an increasing number of SNPs.

[00142] FIGs. 8A-8D are graphs showing the distribution of S/T for various copy number hypotheses for a DOR of 1000 and tumor fraction of 1% for an increasing number of SNPs.

[00143] FIGs. 9A-9D are graphs showing the distribution of S/T for various copy number hypotheses for a DOR of 1000 and tumor fraction of 2% for an increasing number of SNPs.

[00144] FIGs. 10A-10D are graphs showing the distribution of S/T for various copy number hypotheses for a DOR of 1000 and tumor fraction of 3% for an increasing number of SNPs.

[00145] FIGs. 11A-11D are graphs showing the distribution of S/T for various copy number hypotheses for a DOR of 1000 and tumor fraction of 4% for an increasing number of SNPs.

[00146] FIGs. 12A-12D are graphs showing the distribution of S/T for various copy number hypotheses for a DOR of 3000 and tumor fraction of 0.5% for an increasing number of SNPs.

[00147] FIGs. 13A-13D are graphs showing the distribution of S/T for various copy number hypotheses for a DOR of 3000 and tumor fraction of 1% for an increasing number of SNPs.

[00148] FIG. 14 is a table indicating the sensitivity and specificity for detecting six microdeletion syndromes.

[00149] FIGs. 15A-15C are graphical representations of euploidy. The x-axis represents the linear position of the individual polymorphic loci along the chromosome, and the y-axis represents the number of A allele reads as a fraction of the total (A+B) allele reads. Maternal and fetal genotypes are indicated to the right of the plots. The plots are color-coded according to maternal genotype, such that red indicates a maternal genotype of AA, blue indicates a maternal genotype of BB, and green indicates a maternal genotype of AB. FIG. 15A is a plot of when two chromosomes are present, and the fetal cfDNA fraction is 0%. This plot is from a non-pregnant

woman, and thus represents the pattern when the genotype is entirely maternal. Allele clusters are thus centered around 1 (AA alleles), 0.5 (AB alleles), and 0 (BB alleles). FIG. 15B is a plot of when two chromosomes are present, and the fetal fraction is 12%. The contribution of fetal alleles to the fraction of A allele reads shifts the position of some allele spots up or down along the y-axis. FIG. 15C is a plot of when two chromosomes are present, and the fetal fraction is 26%. The pattern, including two red and two blue peripheral bands and a trio of central green bands, is readily apparent.

[00150] FIGs. 16A and 16B are graphical representations of 22q11.2 deletion syndrome. FIG. 16A is for maternal 22q11.2 deletion carrier (as indicated by the absence of the green AB SNPs). FIG 16B is for a paternally inherited 22q11 deletion in a fetus (as indicated by the presence of one red and one blue peripheral band). The x-axis represents the linear position of the SNPs, and the y-axis indicates the fraction of A allele reads out of the total reads. Each spot represents a single SNP locus.

[00151] FIG. 17 is a graphical representation of maternally inherited Cri-du-Chat deletion syndrome (as indicated by the presence of two central green bands instead of three green bands). The x-axis represents the linear position of the SNPs, and the y-axis indicates the fraction of A allele reads out of the total reads. Each spot represents a single SNP locus.

[00152] FIG. 18 is a graphical representation of paternally inherited Wolf-Hirschhorn deletion syndrome (as indicated by the presence of one red and one blue peripheral band). The x-axis represents the linear position of the SNPs, and the y-axis indicates the fraction of A allele reads out of the total reads. Each spot represents a single SNP locus.

[00153] FIGs. 19A-19D are graphical representations of X chromosome spike-in experiments to represent an extra copy of a chromosome or chromosome segment. The plots show different amounts of DNA from a father mixed with DNA from the daughter: 16% father DNA (FIG. 19A), 10% father DNA (FIG. 19B), 1% father DNA (FIG. 19C), and 0.1% father DNA (FIG. 19D). The x-axis represents the linear position of the SNPs on the X chromosome, and the y-axis indicates the fraction of M allele reads out of the total reads (M + R). Each spot represents a single SNP locus with allele M or R.

[00154] FIGs. 20A and 20B are graphs of the false negative rate using haplotype data (FIG. 20A) and without haplotype data (FIG. 20B).

[00155] FIGs. 21A and 21B are graphs of the false positive rate for $p = 1\%$ using haplotype data (FIG. 21A) and without haplotype data (FIG. 21B).

[00156] FIGs. 22A and 22B are graphs of the false positive rate for $p = 1.5\%$ using haplotype data (FIG. 22A) and without haplotype data (FIG. 22B).

[00157] FIGs. 23A and 23B are graphs of the false positive rate for $p = 2\%$ using haplotype data (FIG. 23A) and without haplotype data (FIG. 23B).

[00158] FIGs. 24A and 24B are graphs of the false positive rate for $p = 2.5\%$ using haplotype data (FIG. 24A) and without haplotype data (FIG. 24B).

[00159] FIGs. 25A and 25B are graphs of the false positive rate for $p = 3\%$ using haplotype data (FIG. 25A) and without haplotype data (FIG. 25B).

[00160] FIG. 26 is a table of false positive rates for the first simulation.

[00161] FIG. 27 is a table of false negative rates for the first simulation.

[00162] While the above-identified drawings set forth presently disclosed embodiments, other embodiments are also contemplated, as noted in the discussion. This disclosure presents illustrative embodiments by way of representation and not limitation. Numerous other modifications and embodiments can be devised by those skilled in the art which fall within the scope and spirit of the principles of the presently disclosed embodiments.

DETAILED DESCRIPTION OF THE INVENTION

[00163] The present invention generally relates, at least in part, to improved methods of determining the presence or absence of copy number variations, such as deletions or duplications of chromosome segments or entire chromosomes. The methods are particularly useful for detecting small deletions or duplications, which can be difficult to detect with high specificity and sensitivity using prior methods due to the small amount of data available from the relevant chromosome segment. Methods of the invention can also be used to detect deletions or duplications that are only present in a small percentage of the cells or nucleic acid molecules that are tested. This allows deletions or duplications to be detected prior to the occurrence of disease (such as at a precancerous stage) or in the early stages of disease, such as before a large number of diseased cells (such as cancer cells) with the deletion or duplication accumulate. The more accurate detection of deletions or duplications associated with a disease or disorder enable improved methods for diagnosing, prognosticating, preventing, delaying, stabilizing, or treating

the disease or disorder. Several deletions or duplications are known to be associated with cancer or with severe mental or physical handicaps.

[00164] Successful treatment of a disease such as cancer often relies on early diagnosis, correct staging of the disease, selection of an effective therapeutic regimen, and close monitoring to prevent or detect relapse. For cancer diagnosis, histological evaluation of tumor material obtained from tissue biopsy is often considered the most reliable method. However, the invasive nature of biopsy-based sampling has rendered it impractical for mass screening and regular follow up. Therefore, the present methods have the advantage of being able to be performed non-invasively if desired for relatively low cost with fast turnaround time. The targeted sequencing that may be used by the methods of the invention requires less reads than shotgun sequencing, such as a few million reads instead of 40 million reads, thereby decreasing cost. The multiplex PCR and next generation sequencing that may be used increase throughput and reduces costs.

[00165] In some embodiments, the methods are used to detect a deletion or duplication in an individual. A sample from the individual that contains cells or nucleic acids suspected of having a deletion or duplication may be analyzed. In some embodiments, the sample is from a tissue or organ suspected of having a deletion or duplication, such as cells or a mass suspected of being cancerous. The methods of the invention can be used to detect deletions or duplications that are only present in one cell or a small number of cells in a mixture containing cells with the deletion or duplication and cells without the deletion or duplication. In some embodiments, cfDNA or cfRNA from a blood sample from the individual is analyzed. In some embodiments, cfDNA or cfRNA is secreted by cells, such as cancer cells. In some embodiments, cfDNA or cfRNA is released by cells undergoing necrosis or apoptosis, such as cancer cells. The methods of the invention can be used to detect deletions or duplications that are only present in a small percentage of the cfDNA or cfRNA. In some embodiments, one or more cells from an embryo are tested.

[00166] In some embodiments, the methods are used for non-invasive or invasive prenatal testing of a fetus. These methods can be used to determine the presence or absence of deletions or duplications of a chromosome segment or an entire chromosome, such as deletions or duplications known to be associated severe mental or physical handicaps, learning disabilities, or cancer. In some embodiments for non-invasive prenatal testing (NIPT), cells, cfDNA or cfRNA

from a blood sample from the pregnant mother is tested. The methods allow the detection of a deletion or duplication in the cells, cfDNA, or cfRNA from the fetus despite the large amount of cells, cfDNA, or cfRNA from the mother that is also present. In some embodiments for invasive prenatal testing, DNA or RNA from a sample from the fetus is tested (such as a CVS or amniocentesis sample). Even if the sample is contaminated with DNA or RNA from the pregnant mother, the methods can be used to detect a deletion or duplication in the fetal DNA or RNA.

[00167] In addition to determining the presence or absence of copy number variation, one or more other factors can be analyzed if desired. These factors can be used to increase the accuracy of the diagnosis (such as determining the presence or absence of cancer or an increased risk for cancer, classifying the cancer, or staging the cancer) or prognosis. These factors can also be used to select a particular therapy or treatment regimen that is likely to be effective in the subject. Exemplary factors include the presence or absence of polymorphisms or mutation; altered (increased or decreased) levels of total or particular cfDNA, cfRNA, microRNA (miRNA); altered (increased or decreased) methylation levels, altered (increased or decreased) DNA integrity, altered (increased or decreased) or alternative mRNA splicing.

[00168] The following sections describe methods for detecting deletions or duplications using phased or unphased data; samples that can be tested; methods for sample preparation, amplification, and quantification; methods for phasing genetic data; polymorphisms, mutations, nucleic acid alterations, mRNA splicing alterations, and changes in nucleic acid levels that can be detected; databases with results from the methods, other risk factors and screening methods; cancers that can be diagnosed or treated; cancer treatments; cancer models for testing treatments; and methods for formulating and administering treatments.

Exemplary Methods for Detecting Deletions and Duplications Using Phased Data

[00169] In some embodiments, phased genetic data is used to determine if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in the genome of an individual (such as in the genome of one or more cells or in cfDNA or cfRNA). Exemplary overrepresentations include the duplication of the first homologous chromosome segment or the deletion of the second homologous chromosome segment. In some embodiments, there is not an

overrepresentation since the first and homologous chromosome segments are present in equal proportions (such as one copy of each segment in a diploid sample). In some embodiments, calculated allele ratios in a nucleic acid sample are compared to expected allele ratios to determine if there is an overrepresentation as described further below.

[00170] In some embodiments, the method includes obtaining phased genetic data for the first homologous chromosome segment comprising the identity of the allele present at that locus on the first homologous chromosome segment for each locus in a set of polymorphic loci on the first homologous chromosome segment, obtaining phased genetic data for the second homologous chromosome segment comprising the identity of the allele present at that locus on the second homologous chromosome segment for each locus in the set of polymorphic loci on the second homologous chromosome segment, and obtaining measured genetic allelic data comprising, for each of the alleles at each of the loci in the set of polymorphic loci, the amount of each allele present in a sample of DNA or RNA from one or more target cells and one or more non-target cells from the individual. In some embodiments, the method includes enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment; calculating, for each of the hypotheses, expected genetic data for the plurality of loci in the sample from the obtained phased genetic data for one or more possible ratios of DNA or RNA from the one or more target cells to the total DNA or RNA in the sample; calculating (such as calculating on a computer) for each possible ratio of DNA or RNA and for each hypothesis, the data fit between the obtained genetic data of the sample and the expected genetic data for the sample for that possible ratio of DNA or RNA and for that hypothesis; ranking one or more of the hypotheses according to the data fit; and selecting the hypothesis that is ranked the highest, thereby determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment in the genome of one or more cells from the individual.

[00171] In one aspect, the invention features a method for determining a number of copies of a chromosome or chromosome segment of interest in the genome of a fetus. In some embodiments, the method includes obtaining phased genetic data for at least one biological parent of the fetus, wherein the phased genetic data comprises the identity of the allele present for each locus in a set of polymorphic loci on a first homologous chromosome segment and a second homologous chromosome segment in the parent. In some embodiments,

the method includes obtaining genetic data at the set of polymorphic loci on the chromosome or chromosome segment in a mixed sample of DNA or RNA comprising fetal DNA or RNA and maternal DNA or RNA from the mother of the fetus by measuring the quantity of each allele at each locus. In some embodiments, the method includes enumerating a set of one or more hypotheses specifying the number of copies of the chromosome or chromosome segment of interest present in the genome of the fetus. In some embodiments, the method includes creating (such as creating on a computer) for each of the hypotheses, a probability distribution of the expected quantity of each allele at each of the plurality of loci in mixed sample from the (i) the obtained phased genetic data from the parent(s) and optionally (ii) the probability of one or more crossovers that may have occurred during the formation of a gamete that contributed a copy of the chromosome or chromosome segment of interest to the fetus; calculating (such as calculating on a computer) a fit, for each of the hypotheses, between (1) the obtained genetic data of the mixed sample and (2) the probability distribution of the expected quantity of each allele at each of the plurality of loci in mixed sample for that hypothesis; ranking one or more of the hypotheses according to the data fit; and selecting the hypothesis that is ranked the highest, thereby determining the number of copies of the chromosome segment of interest in the genome of the fetus.

[00172] In some embodiments, the method involves obtaining phased genetic data using any of the methods described herein or any known method. In some embodiments, the method involves simultaneously or sequentially in any order (i) obtaining phased genetic data for the first homologous chromosome segment comprising the identity of the allele present at that locus on the first homologous chromosome segment for each locus in a set of polymorphic loci on the first homologous chromosome segment, (ii) obtaining phased genetic data for the second homologous chromosome segment comprising the identity of the allele present at that locus on the second homologous chromosome segment for each locus in the set of polymorphic loci on the second homologous chromosome segment, and (iii) obtaining measured genetic allelic data comprising the amount of each allele at each of the loci in the set of polymorphic loci in a sample of DNA from one or more cells from the individual.

[00173] In some embodiments, the method involves calculating allele ratios for one or more loci in the set of polymorphic loci that are heterozygous in at least one cell from which the sample was derived (such as the loci that are heterozygous in the fetus and/or heterozygous in the

mother). In some embodiments, the calculated allele ratio for a particular locus is the measured quantity of one of the alleles divided by the total measured quantity of all the alleles for the locus. In some embodiments, the calculated allele ratio for a particular locus is the measured quantity of one of the alleles (such as the allele on the first homologous chromosome segment) divided by the measured quantity of one or more other alleles (such as the allele on the second homologous chromosome segment) for the locus. The calculated allele ratios may be calculated using any of the methods described herein or any standard method (such as any mathematical transformation of the calculated allele ratios described herein).

[00174] In some embodiments, the method involves determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment by comparing one or more calculated allele ratios for a locus to an allele ratio that is expected for that locus if the first and second homologous chromosome segments are present in equal proportions. In some embodiments, the expected allele ratio assumes the possible alleles for a locus have an equal likelihood of being present. In some embodiments in which the calculated allele ratio for a particular locus is the measured quantity of one of the alleles divided by the total measured quantity of all the alleles for the locus, the corresponding expected allele ratio is 0.5 for a biallelic locus, or 1/3 for a triallelic locus. In some embodiments, the expected allele ratio is the same for all the loci, such as 0.5 for all loci. In some embodiments, the expected allele ratio assumes that the possible alleles for a locus can have a different likelihood of being present, such as the likelihood based on the frequency of each of the alleles in a particular population that the subject belongs in, such as a population based on the ancestry of the subject. Such allele frequencies are publicly available (*see, e.g.,* HapMap Project; Perlegen Human Haplotype Project; web at ncbi.nlm.nih.gov/projects/SNP/; Sherry ST, Ward MH, Kholodov M, et al. dbSNP: the NCBI database of genetic variation. *Nucleic Acids Res.* 2001 Jan 1;29(1):308-11, which are each incorporated by reference in its entirety). In some embodiments, the expected allele ratio is the allele ratio that is expected for the particular individual being tested for a particular hypothesis specifying the degree of overrepresentation of the first homologous chromosome segment. For example, the expected allele ratio for a particular individual may be determined based on phased or unphased genetic data from the individual (such as from a sample from the individual that is unlikely to have a deletion or duplication such as a noncancerous sample) or data from one or more relatives from the individual. In some embodiments for

prenatal testing, the expected allele ratio is the allele ratio that is expected for a mixed sample that includes DNA or RNA from the pregnant mother and the fetus (such as a maternal plasma or serum sample that includes cfDNA from the mother and cfDNA from the fetus) for a particular hypothesis specifying the degree of overrepresentation of the first homologous chromosome segment. For example, the expected allele ratio for the mixed sample may be determined based on genetic data from the mother and predicted genetic data for the fetus (such as predictions for alleles that the fetus may have inherited from the mother and/or father). In some embodiments, phased or unphased genetic data from a sample of DNA or RNA from only the mother (such as the buffy coat from a maternal blood sample) is to determine the alleles from the maternal DNA or RNA in the mixed sample as well as alleles that the fetus may have been inherited from the mother (and thus may be present in the fetal DNA or RNA in the mixed sample). In some embodiments, phased or unphased genetic data from a sample of DNA or RNA from only the father is used to determine the alleles that the fetus may have been inherited from the father (and thus may be present in the fetal DNA or RNA in the mixed sample). The expected allele ratios may be calculated using any of the methods described herein or any standard method (such as any mathematical transformation of the expected allele ratios described herein) (U.S. Publication No 2012/0270212, filed Nov. 18, 2011, which is hereby incorporated by reference in its entirety).

[00175] In some embodiments, a calculated allele ratio is indicative of an overrepresentation of the number of copies of the first homologous chromosome segment if either (i) the allele ratio for the measured quantity of the allele present at that locus on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus is greater than the expected allele ratio for that locus, or (ii) the allele ratio for the measured quantity of the allele present at that locus on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than the expected allele ratio for that locus. In some embodiments, a calculated allele ratio is only considered indicative of overrepresentation if it is significantly greater or lower than the expected ratio for that locus. In some embodiments, a calculated allele ratio is indicative of no overrepresentation of the number of copies of the first homologous chromosome segment if either (i) the allele ratio for the measured quantity of the allele present at that locus on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than or equal to the expected allele ratio for that

locus, or (ii) the allele ratio for the measured quantity of the allele present at that locus on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is greater than or equal to the expected allele ratio for that locus. In some embodiments, calculated ratios equal to the corresponding expected ratio are ignored (since they are indicative of no overrepresentation).

[00176] In various embodiments, one or more of the following methods is used to compare one or more of the calculated allele ratios to the corresponding expected allele ratio(s). In some embodiments, one determines whether the calculated allele ratio is above or below the expected allele ratio for a particular locus irrespective of the magnitude of the difference. In some embodiments, one determines the magnitude of the difference between the calculated allele ratio and the expected allele ratio for a particular locus irrespective of whether the calculated allele ratio is above or below the expected allele ratio. In some embodiments, one determines whether the calculated allele ratio is above or below the expected allele ratio and the magnitude of the difference for a particular locus. In some embodiments, one determines whether the average or weighted average value of the calculated allele ratios is above or below the average or weighted average value of the expected allele ratios irrespective of the magnitude of the difference. In some embodiments, one determines the magnitude of the difference between the average or weighted average value of the calculated allele ratios and the average or weighted average value of the expected allele ratios irrespective of whether the average or weighted average of the calculated allele ratio is above or below the average or weighted average value of the expected allele ratio. In some embodiments, one determines whether the average or weighted average value of the calculated allele ratios is above or below the average or weighted average value of the expected allele ratios and the magnitude of the difference. In some embodiments, one determines an average or weighted average value of the magnitude of the difference between the calculated allele ratios and the expected allele ratios.

[00177] In some embodiments, the magnitude of the difference between the calculated allele ratio and the expected allele ratio for one or more loci is used to determine whether the overrepresentation of the number of copies of the first homologous chromosome segment is due to a duplication of the first homologous chromosome segment or a deletion of the second homologous chromosome segment in the genome of one or more of the cells.

[00178] In some embodiments, an overrepresentation of the number of copies of the first homologous chromosome segment is determined to be present if one or more of following conditions is met. In some embodiments, the number of calculated allele ratios that are indicative of an overrepresentation of the number of copies of the first homologous chromosome segment is above a threshold value. In some embodiments, the number of calculated allele ratios that are indicative of no overrepresentation of the number of copies of the first homologous chromosome segment is below a threshold value. In some embodiments, the magnitude of the difference between the calculated allele ratios that are indicative of an overrepresentation of the number of copies of the first homologous chromosome segment and the corresponding expected allele ratios is above a threshold value. In some embodiments, for all calculated allele ratios that are indicative of overrepresentation, the sum of the magnitude of the difference between a calculated allele ratio and the corresponding expected allele ratio is above a threshold value. In some embodiments, the magnitude of the difference between the calculated allele ratios that are indicative of no overrepresentation of the number of copies of the first homologous chromosome segment and the corresponding expected allele ratios is below a threshold value. In some embodiments, the average or weighted average value of the calculated allele ratios for the measured quantity of the allele present on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus is greater than the average or weighted average value of the expected allele ratios by at least a threshold value. In some embodiments, the average or weighted average value of the calculated allele ratios for the measured quantity of the allele present on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than the average or weighted average value of the expected allele ratios by at least a threshold value. In some embodiments, the data fit between the calculated allele ratios and allele ratios that are predicted for an overrepresentation of the number of copies of the first homologous chromosome segment is below a threshold value (indicative of a good data fit). In some embodiments, the data fit between the calculated allele ratios and allele ratios that are predicted for no overrepresentation of the number of copies of the first homologous chromosome segment is above a threshold value (indicative of a poor data fit).

[00179] In some embodiments, an overrepresentation of the number of copies of the first homologous chromosome segment is determined to be absent if one or more of following conditions is met. In some embodiments, the number of calculated allele ratios that are

indicative of an overrepresentation of the number of copies of the first homologous chromosome segment is below a threshold value. In some embodiments, the number of calculated allele ratios that are indicative of no overrepresentation of the number of copies of the first homologous chromosome segment is above a threshold value. In some embodiments, the magnitude of the difference between the calculated allele ratios that are indicative of an overrepresentation of the number of copies of the first homologous chromosome segment and the corresponding expected allele ratios is below a threshold value. In some embodiments, the magnitude of the difference between the calculated allele ratios that are indicative of no overrepresentation of the number of copies of the first homologous chromosome segment and the corresponding expected allele ratios is above a threshold value. In some embodiments, the average or weighted average value of the calculated allele ratios for the measured quantity of the allele present on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus minus the average or weighted average value of the expected allele ratios is less than a threshold value. In some embodiments, the average or weighted average value of the expected allele ratios minus the average or weighted average value of the calculated allele ratios for the measured quantity of the allele present on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than a threshold value. In some embodiments, the data fit between the calculated allele ratios and allele ratios that are predicted for an overrepresentation of the number of copies of the first homologous chromosome segment is above a threshold value. In some embodiments, the data fit between the calculated allele ratios and allele ratios that are predicted for no overrepresentation of the number of copies of the first homologous chromosome segment is below a threshold value. In some embodiments, the threshold is determined from empirical testing of samples known to have a CNV of interest and/or samples known to lack the CNV.

[00180] In some embodiments, determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment includes enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment. One exemplary hypothesis is the absence of an overrepresentation since the first and homologous chromosome segments are present in equal proportions (such as one copy of each segment in a diploid sample). Other exemplary hypotheses include the first homologous chromosome segment being duplicated one or more times (such as 1, 2, 3, 4, 5, or more extra

copies of the first homologous chromosome compared to the number of copies of the second homologous chromosome segment). Another exemplary hypothesis includes the deletion of the second homologous chromosome segment. Yet another exemplary hypothesis is the deletion of both the first and the second homologous chromosome segments. In some embodiments, predicted allele ratios for the loci that are heterozygous in at least one cell (such as the loci that are heterozygous in the fetus and/or heterozygous in the mother) are estimated for each hypothesis given the degree of overrepresentation specified by that hypothesis. In some embodiments, the likelihood that the hypothesis is correct is calculated by comparing the calculated allele ratios to the predicted allele ratios, and the hypothesis with the greatest likelihood is selected.

[00181] In some embodiments, an expected distribution of a test statistic is calculated using the predicted allele ratios for each hypothesis. In some embodiments, the likelihood that the hypothesis is correct is calculated by comparing a test statistic that is calculated using the calculated allele ratios to the expected distribution of the test statistic that is calculated using the predicted allele ratios, and the hypothesis with the greatest likelihood is selected.

[00182] In some embodiments, predicted allele ratios for the loci that are heterozygous in at least one cell (such as the loci that are heterozygous in the fetus and/or heterozygous in the mother) are estimated given the phased genetic data for the first homologous chromosome segment, the phased genetic data for the second homologous chromosome segment, and the degree of overrepresentation specified by that hypothesis. In some embodiments, the likelihood that the hypothesis is correct is calculated by comparing the calculated allele ratios to the predicted allele ratios; and the hypothesis with the greatest likelihood is selected.

Use of Fraction of CNV or Disease in Mixed Samples

[00183] In some embodiments, the sample is a mixed sample with DNA or RNA from one or more target cells and one or more non-target cells. In some embodiments, the target cells are cells that have a CNV, such as a deletion or duplication of interest, and the non-target cells are cells that do not have the copy number variation of interest (such as a mixture of cells with the deletion or duplication of interest and cells without any of the deletions or duplications being tested). In some embodiments, the target cells are cells that are associated with a disease or disorder or an increased risk for disease or disorder (such as cancer cells), and the non-target

cells are cells that are not associated with a disease or disorder or an increased risk for disease or disorder (such as noncancerous cells). In some embodiments, the target cells all have the same CNV. In some embodiments, two or more target cells have different CNVs. In some embodiments, one or more of the target cells has a CNV, polymorphism, or mutation associated with the disease or disorder or an increased risk for disease or disorder that is not found in at least one other target cell. In some such embodiments, the fraction of the cells that are associated with the disease or disorder or an increased risk for disease or disorder out of the total cells from a sample is assumed to be greater than or equal to the fraction of the most frequent of these CNVs, polymorphisms, or mutations in the sample. For example if 6% of the cells have a K-ras mutation, and 8% of the cells have a BRAF mutation, at least 8% of the cells are assumed to be cancerous.

[00184] In some embodiments, the ratio of DNA (or RNA) from the one or more target cells to the total DNA (or RNA) in the sample is calculated. In some embodiments, a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment are enumerated. In some embodiments, predicted allele ratios for the loci that are heterozygous in at least one cell (such as the loci that are heterozygous in the fetus and/or heterozygous in the mother) are estimated given the calculated ratio of DNA or RNA and the degree of overrepresentation specified by that hypothesis are estimated for each hypothesis. In some embodiments, the likelihood that the hypothesis is correct is calculated by comparing the calculated allele ratios to the predicted allele ratios, and the hypothesis with the greatest likelihood is selected.

[00185] In some embodiments, an expected distribution of a test statistic calculated using the predicted allele ratios and the calculated ratio of DNA or RNA is estimated for each hypothesis. In some embodiments, the likelihood that the hypothesis is correct is determined by comparing a test statistic calculated using the calculated allele ratios and the calculated ratio of DNA or RNA to the expected distribution of the test statistic calculated using the predicted allele ratios and the calculated ratio of DNA or RNA, and the hypothesis with the greatest likelihood is selected.

[00186] In some embodiments, the method includes enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment. In some embodiments, the method includes estimating, for each hypothesis, either (i) predicted allele ratios for the loci that are heterozygous in at least one cell (such as the loci that are

heterozygous in the fetus and/or heterozygous in the mother) given the degree of overrepresentation specified by that hypothesis or (ii) for one or more possible ratios of DNA or RNA, an expected distribution of a test statistic calculated using the predicted allele ratios and the possible ratio of DNA or RNA from the one or more target cells to the total DNA or RNA in the sample. In some embodiments, a data fit is calculated by comparing either (i) the calculated allele ratios to the predicted allele ratios, or (ii) a test statistic calculated using the calculated allele ratios and the possible ratio of DNA or RNA to the expected distribution of the test statistic calculated using the predicted allele ratios and the possible ratio of DNA or RNA. In some embodiments, one or more of the hypotheses are ranked according to the data fit, and the hypothesis that is ranked the highest is selected. In some embodiments, a technique or algorithm, such as a search algorithm, is used for one or more of the following steps: calculating the data fit, ranking the hypotheses, or selecting the hypothesis that is ranked the highest. In some embodiments, the data fit is a fit to a beta-binomial distribution or a fit to a binomial distribution. In some embodiments, the technique or algorithm is selected from the group consisting of maximum likelihood estimation, maximum a-posteriori estimation, Bayesian estimation, dynamic estimation (such as dynamic Bayesian estimation), and expectation-maximization estimation. In some embodiments, the method includes applying the technique or algorithm to the obtained genetic data and the expected genetic data.

[00187] In some embodiments, the method includes creating a partition of possible ratios that range from a lower limit to an upper limit for the ratio of DNA or RNA from the one or more target cells to the total DNA or RNA in the sample. In some embodiments, a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment are enumerated. In some embodiments, the method includes estimating, for each of the possible ratios of DNA or RNA in the partition and for each hypothesis, either (i) predicted allele ratios for the loci that are heterozygous in at least one cell (such as the loci that are heterozygous in the fetus and/or heterozygous in the mother) given the possible ratio of DNA or RNA and the degree of overrepresentation specified by that hypothesis or (ii) an expected distribution of a test statistic calculated using the predicted allele ratios and the possible ratio of DNA or RNA. In some embodiments, the method includes calculating, for each of the possible ratios of DNA or RNA in the partition and for each hypothesis, the likelihood that the hypothesis is correct by comparing either (i) the

calculated allele ratios to the predicted allele ratios, or (ii) a test statistic calculated using the calculated allele ratios and the possible ratio of DNA or RNA to the expected distribution of the test statistic calculated using the predicted allele ratios and the possible ratio of DNA or RNA. In some embodiments, the combined probability for each hypothesis is determined by combining the probabilities of that hypothesis for each of the possible ratios in the partition; and the hypothesis with the greatest combined probability is selected. In some embodiments, the combined probability for each hypothesis is determined by weighting the probability of a hypothesis for a particular possible ratio based on the likelihood that the possible ratio is the correct ratio.

[00188] In some embodiments, a technique selected from the group consisting of maximum likelihood estimation, maximum a-posteriori estimation, Bayesian estimation, dynamic estimation (such as dynamic Bayesian estimation), and expectation-maximization estimation is used to estimate the ratio of DNA or RNA from the one or more target cells to the total DNA or RNA in the sample.

Exemplary Methods for Using Imperfectly Phased Data

[00189] In some embodiments, imperfectly phased data is used. For example, it may not be known with 100% certainty which allele is present for one or more of the loci on the first and/or second homologous chromosome segment. In some embodiments, the phased genetic data comprises probabilistic data for two or more possible sets of phased genetic data, wherein each possible set of phased data comprises a possible identity of the allele present at each locus in the set of polymorphic loci on the first homologous chromosome segment and a possible identity of the allele present at each locus in the set of polymorphic loci on the second homologous chromosome segment. In some embodiments, the probability for at least one of the hypotheses is determined for each of the possible sets of phased genetic data. In some embodiments, the combined probability for the hypothesis is determined by combining the probabilities of the hypothesis for each of the possible sets of phased genetic data; and the hypothesis with the greatest combined probability is selected.

Exemplary Test Statistic for Analysis of Phased Data

[00190] An exemplary test statistic is described below for analysis of phased data from a sample known or suspected of being a mixed sample containing DNA or RNA that originated from two or more cells that are not genetically identical. Let f denote the fraction of DNA or RNA of interest, for example the fraction of DNA or RNA with a CNV of interest, or the fraction of DNA or RNA from cells of interest, such as cancer cells. In some embodiments for prenatal testing, f denotes the fraction of fetal DNA, RNA, or cells in a mixture of fetal and maternal DNA, RNA, or cells. Note that this refers to the fraction of DNA from cells of interest assuming two copies of DNA are given by each cell of interest. This differs from the DNA fraction from cells of interest at a segment that is deleted or duplicated.

[00191] The possible allelic values of each SNP are denoted A and B. AA, AB, BA, and BB are used to denote all possible ordered allele pairs. In some embodiments, SNPs with ordered alleles AB or BA are analyzed. Let N_i denote the number of sequence reads of the i th SNP, and A_i and B_i denote the number of reads of the i th SNP that indicate allele A and B, respectively. It is assumed:

$$N_i = A_i + B_i.$$

The allele ratio R_i is defined:

$$R_i \triangleq \frac{A_i}{N_i}.$$

Let T denote the number of SNPs targeted.

[00192] Without loss of generality, some embodiments focus on a single chromosome segment. In some such embodiments, all of the target SNPs are contained in the segment chromosome of interest. In other embodiments, multiple chromosome segments are analyzed for possible copy number variations.

MAP Estimation

[00193] This method leverages the knowledge of phasing via ordered alleles to detect the deletion or duplication of the target segment. For each SNP i , define

$$X_i \triangleq \begin{cases} 1 & R_i < 0.5 \text{ and SNP } i \text{ AB} \\ 0 & R_i \geq 0.5 \text{ and SNP } i \text{ AB} \\ 0 & R_i < 0.5 \text{ and SNP } i \text{ BA} \\ 1 & R_i \geq 0.5 \text{ and SNP } i \text{ BA} \end{cases}$$

[00194] Then define

$$S \triangleq \sum_{All\ SNPs} X_i.$$

The distributions of the X_i and S under various copy number hypotheses (such as hypotheses for disomy, deletion of the first or second homolog, or duplication of the first or second homolog) are described below.

Disomy Hypothesis

[00195] Under the hypothesis that the target segment is not deleted or duplicated,

$$X_i = \begin{cases} 0 & wp\ 1 - p\left(\frac{1}{2}, N_i\right) \\ 1 & wp\ p\left(\frac{1}{2}, N_i\right) \end{cases}$$

where

$$p(b, n) \triangleq Pr\left\{X \sim Bino(b, n) \geq \frac{n}{2}\right\}.$$

If we assume a constant depth of read N , this gives us a Binomial distribution S with parameters

$$p\left(\frac{1}{2}, N\right) \text{ and } T.$$

Deletion Hypotheses

[00196] Under the hypothesis that the first homolog is deleted (*i.e.*, an AB SNP becomes B, and a BA SNP becomes A), then R_i has a Binomial distribution with parameters $1 - \frac{1}{2-f}$ and T for AB SNPs, and $\frac{1}{2-f}$ and T for BA SNPs. Therefore,

$$X_i = \begin{cases} 0 & wp\ 1 - p\left(\frac{1}{2-f}, N_i\right) \\ 1 & wp\ p\left(\frac{1}{2-f}, N_i\right) \end{cases}$$

If we assume a constant depth of read N , this gives a Binomial distribution S with parameters

$$p\left(\frac{1}{2-f}, N\right) \text{ and } T.$$

[00197] Under the hypothesis that the second homolog is deleted (*i.e.*, an AB SNP becomes A, and a BA SNP becomes B), then R_i has a Binomial distribution with parameters $\frac{1}{2-f}$ and T for AB SNPs, and $1 - \frac{1}{2-f}$ and T for BA SNPs. Therefore,

$$X_i = \begin{cases} 0 & wp \ p\left(\frac{1}{2-f}, N_i\right) \\ 1 & wp \ 1 - p\left(\frac{1}{2-f}, N_i\right) \end{cases}$$

If we assume a constant depth of read N , this gives a Binomial distribution S with parameters

$$1 - p\left(\frac{1}{2-f}, N\right) \text{ and } T.$$

Duplication Hypotheses

[00198] Under the hypothesis that the first homolog is duplicated (*i.e.*, an AB SNP becomes AAB, and a BA SNP becomes BBA), then R_i has a Binomial distribution with parameters $\frac{1+f}{2+f}$ and T for AB SNPs, and $1 - \frac{1+f}{2+f}$ and T for BA SNPs. Therefore,

$$X_i = \begin{cases} 0 & wp \ p\left(\frac{1+f}{2+f}, N_i\right) \\ 1 & wp \ 1 - p\left(\frac{1+f}{2+f}, N_i\right) \end{cases}$$

If we assume a constant depth of read N , this gives us a Binomial distribution S with parameters

$$1 - p\left(\frac{1+f}{2+f}, N\right) \text{ and } T.$$

[00199] Under the hypothesis that the second homolog is duplicated (*i.e.*, an AB SNP becomes ABB, and a BA SNP becomes BAA), then R_i has a Binomial distribution with parameters $1 - \frac{1+f}{2+f}$ and T for AB SNPs, and $\frac{1+f}{2+f}$ and T for BA SNPs. Therefore,

$$X_i = \begin{cases} 0 & \text{wp } 1 - p\left(\frac{1+f}{2+f}, N_i\right) \\ 1 & \text{wp } p\left(\frac{1+f}{2+f}, N_i\right) \end{cases}$$

If we assume a constant depth of read N , this gives a Binomial distribution S with parameters

$$p\left(\frac{1+f}{2+f}, N\right) \text{ and } T.$$

Classification

[00200] As demonstrated in the sections above, X_i is a binary random variable with

$$Pr\{X_1 = 1\} = \begin{cases} p\left(\frac{1}{2}, N_i\right) & \text{given disomy} \\ p\left(\frac{1}{2-f}, N_i\right) & \text{homolog 1 deletion} \\ 1 - p\left(\frac{1}{2-f}, N_i\right) & \text{homolog 2 deletion} \\ 1 - p\left(\frac{1+f}{2+f}, N_i\right) & \text{homolog 1 duplication} \\ p\left(\frac{1+f}{2+f}, N_i\right) & \text{homolog 2 duplication} \end{cases}$$

[00201] This allows one to calculate the probability of the test statistic S under each hypothesis. The probability of each hypothesis given the measured data can be calculated. In some embodiments, the hypothesis with the greatest probability is selected. If desired, the distribution on S can be simplified by either approximating each N_i with a constant depth of reach N or by truncating the depth of reads to a constant N . This simplification gives

$$S \sim \begin{cases} \text{Bino}\left(p\left(\frac{1}{2}, N\right), T\right) & \text{given disomy} \\ \text{Bino}\left(p\left(\frac{1}{2-f}, N\right), T\right) & \text{homolog 1 deletion} \\ \text{Bino}\left(1 - p\left(\frac{1}{2-f}, N\right), T\right) & \text{homolog 2 deletion} \\ \text{Bino}\left(1 - p\left(\frac{1+f}{2+f}, N\right), T\right) & \text{homolog 1 duplication} \\ \text{Bino}\left(p\left(\frac{1+f}{2+f}, N\right), T\right) & \text{homolog 2 duplication} \end{cases}$$

[00202] The value for f can be estimate by selecting the most likely value of f given the measured data, such as the value of f that generates the best data fit using an algorithm (*e.g.*, a search algorithm) such as maximum likelihood estimation, maximum a-posteriori estimation, or Bayesian estimation. In some embodiments, multiple chromosome segments are analyzed and a value for f is estimated based on the data for each segment. If all the target cells have these duplications or deletions, the estimated values for f based on data for these different segments are similar. In some embodiments, f is experimentally measured such as by determining the fraction of DNA or RNA from cancer cells based on methylation differences between cancer and non-cancerous DNA or RNA.

[00203] In some embodiments for mixed samples of fetal and maternal nucleic acids, the value of f is the fetal fraction, that is the fraction of fetal DNA (or RNA) out of the total amount of DNA (or RNA) in the sample. In some embodiments, the fetal fraction is determined by obtaining genotypic data from a maternal blood sample (or fraction thereof) for a set of polymorphic loci on at least one chromosome that is expected to be disomic in both the mother and the fetus; creating a plurality of hypotheses each corresponding to different possible fetal fractions at the chromosome; building a model for the expected allele measurements in the blood sample at the set of polymorphic loci on the chromosome for possible fetal fractions; calculating a relative probability of each of the fetal fractions hypotheses using the model and the allele measurements from the blood sample or fraction thereof; and determining the fetal fraction in the blood sample by selecting the fetal fraction corresponding to the hypothesis with the greatest probability. In some embodiments, the fetal fraction is determined by identifying those polymorphic loci where the mother is homozygous for a first allele at the polymorphic locus, and the father is (i) heterozygous for the first allele and a second allele or (ii) homozygous for a second allele at the polymorphic locus; and using the amount of the second allele detected in the blood sample for each of the identified polymorphic loci to determine the fetal fraction in the blood sample (see, *e.g.*, US Publ. No. 2012/0185176, filed March 29, 2012, and US Pub. No. 2014/0065621, filed March 13, 2013 which are each incorporated herein by reference in their entirety).

[00204] Another exemplary method for determining fetal fraction includes using a high throughput DNA sequencer to count alleles at a large number of polymorphic (such as SNP) genetic loci and modeling the likely fetal fraction (see, for example, US Publ. No.

2012/0264121, which is incorporated herein by reference in its entirety). Another method for calculating fetal fraction can be found in Sparks *et al.*, "Noninvasive prenatal detection and selective analysis of cell-free DNA obtained from maternal blood: evaluation for trisomy 21 and trisomy 18," Am J Obstet Gynecol 2012;206:319.e1-9, which is incorporated herein by reference in its entirety. In some embodiments, fetal fraction is determined using a methylation assay (*see, e.g.*, US Patent Nos. 7,754,428; 7,901,884; and 8,166,382, which are each incorporated herein by reference in their entirety) that assumes certain loci are methylated or preferentially methylated in the fetus, and those same loci are unmethylated or preferentially unmethylated in the mother.

[00205] FIGs. 1A-13D are graphs showing the distribution of the test statistic S divided by T (the number of SNPs) (" S/T ") for various copy number hypotheses for various depth of reads and tumor fractions (where f is the fraction of tumor DNA out of total DNA) for an increasing number of SNPs.

Single Hypothesis Rejection

[00206] The distribution of S for the disomy hypothesis does not depend on f . Thus, the probability of the measured data can be calculated for the disomy hypothesis without calculating f . A single hypothesis rejection test can be used for the null hypothesis of disomy. In some embodiments, the probability of S under the disomy hypothesis is calculated, and the hypothesis of disomy is rejected if the probability is below a given threshold value (such as less than 1 in 1,000). This indicates that a duplication or deletion of the chromosome segment is present. If desired, the false positive rate can be altered by adjusting the threshold value.

Exemplary Methods for Analysis of Phased Data

[00207] Exemplary methods are described below for analysis of data from a sample known or suspected of being a mixed sample containing DNA or RNA that originated from two or more cells that are not genetically identical. In some embodiments, phased data is used. In some embodiments, the method involves determining, for each calculated allele ratio, whether the calculated allele ratio is above or below the expected allele ratio and the magnitude of the difference for a particular locus. In some embodiments, the method involves determining the likelihood that a hypothesis is correct for each locus. In some embodiments, the method

involves determining the likelihood that a hypothesis is correct for each locus and for each possible ratio of DNA or RNA from the one or more target cells to the total DNA or RNA in the sample. In some embodiments, a combined probability for each hypothesis is determined by combining the probabilities of that hypothesis for each locus and each possible ratio, and the hypothesis with the greatest combined probability is selected.

[00208] In one embodiment, the following hypotheses are considered: H_{11} (all cells are normal), H_{10} (presence of cells with only homolog 1, hence homolog 2 deletion), H_{01} (presence of cells with only homolog 2, hence homolog 1 deletion), H_{21} (presence of cells with homolog 1 duplication), H_{12} (presence of cells with homolog 2 duplication). For a fraction f of target cells such as cancer cells or mosaic cells (or the fraction of DNA or RNA from the target cells), the expected allele ratio for heterozygous (AB or BA) SNPs can be found as follows:

$$\begin{aligned}
r(AB, H_{11}) &= r(BA, H_{11}) &= 0.5, \\
r(AB, H_{10}) &= r(BA, H_{01}) &= \frac{1}{2-f}, \\
r(AB, H_{01}) &= r(BA, H_{10}) &= \frac{1-f}{2-f}, \\
r(AB, H_{21}) &= r(BA, H_{12}) &= \frac{1+f}{2+f}, \\
r(AB, H_{12}) &= r(BA, H_{21}) &= \frac{1}{2+f}.
\end{aligned}$$

Bias, Contamination, and Sequencing Error Correction

[00209] The observation at the SNP consists of the number of original mapped reads with each allele present, n_A^o and n_B^o , which sum to the depth of read $n_A^o + n_B^o$. Let $p = \frac{n_A^o}{n_A^o + n_B^o}$. Let E_b denote the expected bias at this SNP. Then, we can find the corrected het rate and reads as follows:

$$\begin{aligned}
\frac{p}{1-p} &= E_b \frac{p'}{1-p'} \Leftrightarrow p' = \frac{1}{1 + E_b \times \frac{1-p}{p}}. \\
n_A &= p' \times (n_A^o + n_B^o), \\
n_B &= n_A^o + n_B^o - n_A.
\end{aligned}$$

[00210] Use c_a to denote the ambient contamination (such as contamination from DNA in the air or environment) and r_{c_a} to denote the allele ratio for the ambient contaminant (which is taken to be 0.5 initially). Moreover, c_g denotes the genotyped contamination rate (such as the contamination from another sample), and $r_{c_g} \in \{0, 0.5, 1\}$ is the allele ratio for the contaminant. Let $s_e^{(r,m)}$ and

$s_e^{(m,r)}$ denote the sequencing errors for calling one allele a different allele (such as by erroneously detecting an A allele when a B allele is present).

[00211] One can find the observed allele ratio q for a given expected allele ratio r as follows:

$$q(r, c_a, r_{c_a}, c_g, r_{c_g}) = \left(r(1 - s_e^{(r,m)}) + (1 - r)s_e^{(m,r)} \right) (1 - c_a - c_g) + \left(r_{c_a}(1 - s_e^{(r,m)}) + (1 - r_{c_a})s_e^{(m,r)} \right) c_a + \left(r_{c_g}(1 - s_e^{(r,m)}) + (1 - r_{c_g})s_e^{(m,r)} \right) c_g. \quad (1)$$

[00212] Since the contaminant genotypes are unknown, population frequencies can be used to find $P(r_{c_g})$. More specifically, let p be the population frequency for one of the alleles (which may be referred to as a reference allele). Then, we have $P(r_{c_g} = 0) = (1 - p)^2$, $P(r_{c_g} = 0.5) = 2p(1 - p)$, and $P(r_{c_g} = 1) = p^2$. The conditional expectation over r_{c_g} in the equation above can be used to determine the $E[q(r, c_a, r_{c_a}, c_g, r_{c_g})]$. Note that the ambient and genotyped contamination are determined using the homozygous SNPs, hence they are not affected by the absence or presence of deletions or duplications. Moreover, it is possible to measure the ambient and genotyped contamination using a reference chromosome if desired.

Likelihood at Each SNP

[00213] The equation below gives the probability of observing n_A and n_B given an expected allele ratio r :

$$P(n_A, n_B | r) = p_{bino}(n_A; n_A + n_B, r) = \binom{n_A + n_B}{n_A} r^{n_A} (1 - r)^{n_B}. \quad (2)$$

[00214] Let D_s denote the data for SNP s . For each hypothesis $h \in H = \{H_{11}, H_{10}, H_{01}, H_{21}, H_{12}\}$, one can let $r = r(AB, h)$ or $r = r(BA, h)$ in the equation (1) and find the conditional expectation over r_{c_g} to determine the observed allele ratio $E[q(r, c_a, r_{c_a}, c_g, r_{c_g})]$. Then, letting $r = E[q(r, c_a, r_{c_a}, c_g, r_{c_g})]$ in equation (2) one can determine $P(D_s | h, f)$.

Search Algorithm

[00215] In some embodiments, SNPs with allele ratios that seem to be outliers are ignored (such as by ignoring or eliminating SNPs with allele ratios that are at least 2 or 3 standard deviations above or below the mean value). Note that in the presence of higher mosaicism percentage,

the variability in the allele ratios may be high, hence this ensures that SNPs will not be trimmed due to mosaicism.

[00216] Let $F = \{f_1, \dots, f_{N_f}\}$ denote the search space for the mosaicism percentage (such as the tumor fraction). One can determine $P(D_s|h, f)$ at each SNP s and $f \in F$, and combine the log likelihood over all SNPs.

[00217] The algorithm goes over each f for each hypothesis. Using a search method, one concludes that mosaicism exists if there is a range F^* of f where the confidence of the deletion or duplication hypothesis is higher than the confidence of the no deletion and no duplication hypotheses. In some embodiments, the maximum likelihood estimate for $P(D_s|h, f)$ in F^* is determined. If desired, the conditional expectation over $f \in F^*$ may be determined. If desired, the confidence for each hypothesis can be determined.

Additional Embodiments

[00218] In some embodiments, a beta binomial distribution is used instead of binomial distribution. In some embodiments, the parameters of the beta binomial are estimated using the expected bias and bias variance (over all cycles). In some embodiments, a reference chromosome or chromosome segment is used to determine the sample specific parameters of beta binomial.

Theoretical Performance using Simulations

[00219] If desired, one can evaluate the theoretical performance of the algorithm by randomly assigning number of reference reads to a SNP with given depth of read (DOR). For the normal case, use $p = 0.5$ for the binomial probability parameter, and for deletions or duplications, p is revised accordingly. Exemplary input parameters for each simulation are as follows: (1) number of snps S , (2) constant DOR D per snp, (3) p , and (4) number of experiments.

First Simulation Experiment

[00220] This experiment focused on $S \in \{500, 1000\}$, $D \in \{500, 1000\}$, $p \in \{0\%, 1\%, 2\%, 3\%, 4\%, 5\%\}$, and 1000 random experiments at each setting. We performed 1,000 simulation experiments in each

setting (hence 24,000 experiments with phase, and 24,000 without phase). We simulated the number of reads from a binomial distribution (if desired, other distributions can be used). The false positive rate (in the case of $p = 0\%$) and false negative rate (in the case of $p > 0\%$) were determined both with or without phase information. False positive rates are listed in Figure 26. Note that phase information is very helpful, especially for $S = 1000, D = 1000$. Although for $S = 500, D = 500$, the algorithm has the highest false positive rates with or without phase out of the conditions tested. False negative rates are listed in Figure 27.

[00221] Phase information is particularly useful for low mosaicism percentages ($\leq 3\%$). Without phase information, a high level of false negatives were observed for $p = 1\%$ because the confidence on deletion is determined by assigning equal chance to H_{10} and H_{01} , and a small deviation in favor of one hypothesis is not sufficient to compensate for the low likelihood from the other hypothesis. This applies to duplications as well. Note also that the algorithm seems to be more sensitive to depth of read compared to number of SNPs. For the results with phase information, we assume that perfect phase information is available for a high number of consecutive heterozygous SNPs. If desired, haplotype information can be obtained by probabilistically combining haplotypes on smaller segments.

Second Simulation Experiment

[00222] This experiment focused on $S \in \{100, 200, 300, 400, 500\}$, $D \in \{1000, 2000, 3000, 4000, 5000\}$, $p \in \{0\%, 1\%, 1.5\%, 2\%, 2.5\%, 3\%\}$, and 10000 random experiments at each setting. The false positive rate (in the case of $p = 0\%$) and false negative rate (in the case of $p > 0\%$) were determined both with or without phase information. The false negative rate is below 10% for $D \geq 3000$ and $N \geq 200$ using haplotype information, whereas the same performance is reached for $D = 5000$ and $N \geq 400$ (FIGs. 20A and 20B). The difference between the false negative rate was particularly stark for small mosaicism percentages (FIGs. 21A-25B). For example, when $p = 1\%$, a less than 20% false negative rate is never reached without haplotype data, whereas it is close to 0% for $N \geq 300$ and $D \geq 3000$. For $p = 3\%$, a 0% false negative rate is observed with haplotype data, while $N \geq 300$ and $D \geq 3000$ is needed to reach the same performance without haplotype data.

Exemplary Methods for Detecting Deletions and Duplications Without Phased Data

[00223] In some embodiments, unphased genetic data is used to determine if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in the genome of an individual (such as in the genome of one or more cells or in cfDNA or cfRNA). In some embodiments, phased genetic data is used but the phasing is ignored. In some embodiments, the sample of DNA or RNA is a mixed sample of cfDNA or cfRNA from the individual that includes cfDNA or cfRNA from two or more genetically different cells. In some embodiments, the method utilizes the magnitude of the difference between the calculated allele ratio and the expected allele ratio for each of the loci.

[00224] In some embodiments, the method involves obtaining genetic data at a set of polymorphic loci on the chromosome or chromosome segment in a sample of DNA or RNA from one or more cells from the individual by measuring the quantity of each allele at each locus. In some embodiments, allele ratios are calculated for the loci that are heterozygous in at least one cell from which the sample was derived (such as the loci that are heterozygous in the fetus and/or heterozygous in the mother). In some embodiments, the calculated allele ratio for a particular locus is the measured quantity of one of the alleles divided by the total measured quantity of all the alleles for the locus. In some embodiments, the calculated allele ratio for a particular locus is the measured quantity of one of the alleles (such as the allele on the first homologous chromosome segment) divided by the measured quantity of one or more other alleles (such as the allele on the second homologous chromosome segment) for the locus. The calculated allele ratios and expected allele ratios may be calculated using any of the methods described herein or any standard method (such as any mathematical transformation of the calculated allele ratios or expected allele ratios described herein).

[00225] In some embodiments, a test statistic is calculated based on the magnitude of the difference between the calculated allele ratio and the expected allele ratio for each of the loci. In some embodiments, the test statistic Δ is calculated using the following formula

$$\Delta = \frac{\sum_{All\ Loci} (\delta_i - \mu_i)}{\sqrt{\sum_{All\ Loci} \sigma_i^2}}$$

wherein δ_i is the magnitude of the difference between the calculated allele ratio and the expected allele ratio for the i th loci;

wherein μ_i is the mean value of δ_i ; and

wherein σ_i^2 is the standard deviation of δ_i .

[00226] For example, we can define δ_i as follows when the expected allele ratio is 0.5:

$$\delta_i \triangleq \left| \frac{1}{2} - R_i \right|.$$

Values for μ_i and σ_i can be computed using the fact that R_i is a Binomial random variable. In some embodiments, the standard deviation is assumed to be the same for all the loci. In some embodiments, the average or weighted average value of the standard deviation or an estimate of the standard deviation is used for the value of σ_i^2 . In some embodiments, the test statistic is assumed to have a normal distribution. For example, the central limit theorem implies that the distribution of Δ converges to a standard normal as the number of loci (such as the number of SNPs T) grows large.

[00227] In some embodiments, a set of one or more hypotheses specifying the number of copies of the chromosome or chromosome segment in the genome of one or more of the cells are enumerated. In some embodiments, the hypothesis that is most likely based on the test statistic is selected, thereby determining the number of copies of the chromosome or chromosome segment in the genome of one or more of the cells. In some embodiments, a hypothesis is selected if the probability that the test statistic belongs to a distribution of the test statistic for that hypothesis is above an upper threshold; one or more of the hypotheses is rejected if the probability that the test statistic belongs to the distribution of the test statistic for that hypothesis is below an lower threshold; or a hypothesis is neither selected nor rejected if the probability that the test statistic belongs to the distribution of the test statistic for that hypothesis is between the lower threshold and the upper threshold, or if the probability is not determined with sufficiently high confidence. In some embodiments, an upper and/or lower threshold is determined from an empirical distribution, such as a distribution from training data (such as samples with a known copy number, such as diploid samples or samples known to have a particular deletion or duplication). Such an empirical distribution can be used to select a threshold for a single hypothesis rejection test.

[00228] Note that the test statistic Δ is independent of S and therefore both can be used independently, if desired.

Exemplary Methods for Detecting Deletions and Duplications Using Allele Distributions or Patterns

[00229] This section includes methods for determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment. In some embodiments, the method involves enumerating (i) a plurality of hypotheses specifying the number of copies of the chromosome or chromosome segment that are present in the genome of one or more cells (such as cancer cells) of the individual or (ii) a plurality of hypotheses specifying the degree of overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in the genome of one or more cells of the individual. In some embodiments, the method involves obtaining genetic data from the individual at a plurality of polymorphic loci (such as SNP loci) on the chromosome or chromosome segment. In some embodiments, a probability distribution of the expected genotypes of the individual for each of the hypotheses is created. In some embodiments, a data fit between the obtained genetic data of the individual and the probability distribution of the expected genotypes of the individual is calculated. In some embodiments, one or more hypotheses are ranked according to the data fit, and the hypothesis that is ranked the highest is selected. In some embodiments, a technique or algorithm, such as a search algorithm, is used for one or more of the following steps: calculating the data fit, ranking the hypotheses, or selecting the hypothesis that is ranked the highest. In some embodiments, the data fit is a fit to a beta-binomial distribution or a fit to a binomial distribution. In some embodiments, the technique or algorithm is selected from the group consisting of maximum likelihood estimation, maximum a-posteriori estimation, Bayesian estimation, dynamic estimation (such as dynamic Bayesian estimation), and expectation-maximization estimation. In some embodiments, the method includes applying the technique or algorithm to the obtained genetic data and the expected genetic data.

[00230] In some embodiments, the method involves enumerating (i) a plurality of hypotheses specifying the number of copies of the chromosome or chromosome segment that are present

in the genome of one or more cells (such as cancer cells) of the individual or (ii) a plurality of hypotheses specifying the degree of overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in the genome of one or more cells of the individual. In some embodiments, the method involves obtaining genetic data from the individual at a plurality of polymorphic loci (such as SNP loci) on the chromosome or chromosome segment. In some embodiments, the genetic data includes allele counts for the plurality of polymorphic loci. In some embodiments, a joint distribution model is created for the expected allele counts at the plurality of polymorphic loci on the chromosome or chromosome segment for each hypothesis. In some embodiments, a relative probability for one or more of the hypotheses is determined using the joint distribution model and the allele counts measured on the sample, and the hypothesis with the greatest probability is selected.

[00231] In some embodiments, the distribution or pattern of alleles (such as the pattern of calculated allele ratios) is used to determine the presence or absence of a CNV, such as a deletion or duplication. If desired the parental origin of the CNV can be determined based on this pattern. A maternally inherited duplication is an extra copy of a chromosome segment from the mother, and maternally inherited deletion is the absence of the copy of a chromosome segment from the mother such that the only copy of the chromosome segment that is present is from the father. Exemplary patterns are illustrated in FIGs. 15A-19D and are described further below.

[00232] To determine the presence or absence of a deletion of a chromosome segment of interest, the algorithm considers the distribution of sequence counts from each of two possible alleles at large number of SNPs per chromosome. It is important to note that some embodiments of the algorithm use an approach that does not lend itself to visualization. Thus, for the purposes of illustration, the data is displayed in FIGs. 15A-18 in a simplified fashion as ratios of the two most likely alleles, labeled as A and B, so that the relevant trends can be more readily visualized. This simplified illustration does not take into account some of the possible features of the algorithm. For example, two embodiments for the algorithm that are not possible to illustrate with a method of visualization that displays allele ratios are: 1) the ability to leverage linkage disequilibrium, *i.e.* the influence that a measurement at one SNP has on the likely identity of a neighboring SNP, and 2) the use of non-Gaussian data models that describe the expected distribution of allele measurements at a SNP given platform characteristics and amplification

biases. Also note that a simplified version of the algorithm only considers the two most common alleles at each SNP, ignoring other possible alleles.

[00233] Deletions of interest were detected in genomic and maternal blood samples. In some embodiments, the genomic and maternal plasma samples are analyzed using the multiplex-PCR and sequencing method of Example 1. The genomic DNA syndrome samples tested lacked heterozygous SNPs in the targeted regions, confirming the ability of the assays to distinguish monosomy (affected) from disomy (unaffected). Analysis of cfDNA from a maternal blood sample was able to detect 22q11.2 deletion syndrome, Cri-du-Chat deletion syndrome, and Wolf-Hirschhorn deletion syndrome, as well as the other deletion syndromes in FIG. 14 in the fetus.

[00234] FIGs. 15A-15C depict data that indicate the presence of two chromosomes when the sample is entirely maternal (no fetal cfDNA present, Figure 15A), contains a moderate fetal cfDNA fraction of 12% (Figure 15B), or contains a high fetal cfDNA fraction of 26% (Figure 15C). The x-axis represents the linear position of the individual polymorphic loci along the chromosome, and the y-axis represents the number of A allele reads as a fraction of the total (A+B) allele reads. Maternal and fetal genotypes are indicated to the right of the plots. The plots are color-coded according to maternal genotype, such that red indicates a maternal genotype of AA, blue indicates a maternal genotype of BB, and green indicates a maternal genotype of AB. Note that the measurements are made on total cfDNA isolated from maternal blood, and the cfDNA includes both maternal and fetal cfDNA; thus, each spot represents the combination of the fetal and maternal DNA contribution for that SNP. Therefore, increasing the proportion of maternal cfDNA from 0% to 100% will gradually shift some spots up or down within the plots, depending on the maternal and fetal genotype.

[00235] In all cases, SNPs that are homozygous for the A allele (AA) in both the mother and the fetus are found tightly associated with the upper limit of the plots, as the fraction of A allele reads is high because there should be no B alleles present. Conversely, SNPs that are homozygous for the B allele in both the mother and the fetus are found tightly associated with the lower limit of the plots, as the fraction of A allele reads is low because there should be only B alleles. The spots that are not tightly associated with the upper and lower limits of the plots represent SNPs for which the mother, the fetus, or both are heterozygous; these spots are useful for identifying fetal deletions or duplications, but can also be informative for determining paternal versus maternal inheritance. These spots segregate based on both maternal and fetal

genotypes and fetal fraction, and as such the precise position of each individual spot along the y-axis depends on both stoichiometry and fetal fraction. For example, loci where the mother is AA and the fetus is AB are expected to have a different fraction of A allele reads, and thus different positioning along the y-axis, depending on the fetal fraction.

[00236] FIG. 15A has data for a non-pregnant woman, and thus represents the pattern when the genotype is entirely maternal. This pattern includes “clusters” of spots: a red cluster tightly associated with the top of the plot (SNPs where the maternal genotype is AA), a blue cluster tightly associated with the bottom of the plot (SNPs where the maternal genotype is BB), and a single, centered green cluster (SNPs where the maternal genotype is AB). For FIG. 15B, the contribution of fetal alleles to the fraction of A allele reads shifts the position of some allele spots up or down along the y-axis. For FIG. 15C, the pattern, including two red and two blue peripheral bands and a trio of central green bands, is readily apparent. The three central green bands correspond to SNPs that are heterozygous in the mother, and two “peripheral” bands each at both the top (red) and bottom (blue) of the plots correspond to SNPs that are homozygous in the mother.

[00237] Analysis of a 22q11.2 deletion carrier (a mother with this deletion) is shown in FIG. 16A. The deletion carrier does not have heterozygous SNPs in this region since the carrier only has one copy of this region. Thus, this deletion is indicated by the absence of the green AB SNPs. The analysis of a paternally inherited 22q11 deletion in a fetus is shown in FIG. 16B. When the fetus only inherits a single copy of a chromosome segment (in the case of a paternally inherited deletion, the copy present in the fetus comes from the mother), and thus only inherits a single allele for each locus in this segment, heterozygosity of the fetus is not possible. As such, the only possible fetal SNP identities are A or B. Note the absence of internal peripheral bands. For a paternally inherited deletion, the characteristic pattern includes two central green bands that represent SNPs for which the mother is heterozygous, and only has single peripheral red and blue bands that represent SNPs for which the mother is homozygous, and which remain tightly associated with the upper and lower limits of the plots (1 and 0), respectively.

[00238] Analysis of a maternally inherited Cri-du-Chat deletion syndrome is shown in FIG. 17. There are two central green bands instead of three green bands, and there are two red and two blue peripheral bands.

[00239] FIG. 18 is a plot of a paternally inherited Wolf-Hirschhorn deletion syndrome, as indicated by the presence of one red and one blue peripheral band.

[00240] If desired, similar plots can be generated for a sample from an individual suspected of having a deletion or duplication, such as a CNV associated with cancer. In such plots, the following color coding can be used based on the genotype of cells without the CNV: red indicates a genotype of AA, blue indicates a genotype of BB, and green indicates a genotype of AB. In some embodiments for a deletion, the pattern includes two central green bands that represent SNPs for which the individual is heterozygous (top green band represents AB from cells without the deletion and A from cells with the deletion, and bottom green band represents AB from cells without the deletion and B from cells with the deletion), and only has single peripheral red and blue bands that represent SNPs for which the individual is homozygous, and which remain tightly associated with the upper and lower limits of the plots (1 and 0), respectively. In some embodiments, the separation of the two green bands increases as the fraction of cells, DNA, or RNA with the deletion increases.

Exemplary Counting Methods

[00241] In some embodiments, one or more counting methods are used to detect one or more CNS, such as deletions or duplications of chromosome segments or entire chromosomes. In some embodiments, one or more counting methods are used to determine whether the overrepresentation of the number of copies of the first homologous chromosome segment is due to a duplication of the first homologous chromosome segment or a deletion of the second homologous chromosome segment. Exemplary methods are disclosed, *e.g.* U.S. Publication No. 2007/0184467 and U.S. Patent Nos. 7,888,017; 8,008,018; 8,296,076; or 8,195,415, which are each hereby incorporated by reference in its entirety.

[00242] In some embodiments, the total measured quantity of all the alleles for one or more loci (such as the total amount of a polymorphic or non-polymorphic locus) is compared to a reference amount. In some embodiments, the reference amount is (i) a threshold value or (ii) an expected amount for a particular copy number hypothesis. In some embodiments, the reference amount (for the absence of a CNV) is the total measured quantity of all the alleles for one or more loci for one or more chromosomes or chromosomes segments known or expected to not have a deletion or duplication. In some embodiments, the reference amount (for the presence of a

CNV) is the total measured quantity of all the alleles for one or more loci for one or more chromosomes or chromosomes segments known or expected to have a deletion or duplication. In some embodiments, the reference amount is the total measured quantity of all the alleles for one or more loci for one or more reference chromosomes or chromosome segments. In some embodiments, the reference amount is the mean or median of the values determined for two or more different chromosomes, chromosome segments, or different samples. In some embodiments, random (*e.g.*, massively parallel shotgun sequencing) or targeted sequencing is used to determine the amount of one or more polymorphic or non-polymorphic loci.

[00243] In some embodiments utilizing a reference amount, the method includes (a) measuring the amount of genetic material on a chromosome or chromosome segment of interest; (b) comparing the amount from step (a) to a reference amount; and (c) identifying the presence or absence of a deletion or duplication based on the comparison.

[00244] In some embodiments utilizing a reference chromosome or chromosome segment, the method includes sequencing DNA or RNA from a sample to obtain a plurality of sequence tags aligning to target loci. In some embodiments, the sequence tags are of sufficient length to be assigned to a specific target locus (*e.g.*, 15-100 nucleotides in length); the target loci are from a plurality of different chromosomes or chromosome segments that include at least one first chromosome or chromosome segment suspected of having an abnormal distribution in the sample and at least one second chromosome or chromosome segment presumed to be normally distributed in the sample. In some embodiments, the plurality of sequence tags are assigned to their corresponding target loci. In some embodiments, the number of sequence tags aligning to the target loci of the first chromosome or chromosome segment and the number of sequence tags aligning to the target loci of the second chromosome or chromosome segment are determined. In some embodiments, these numbers are compared to determine the presence or absence of an abnormal distribution (such as a deletion or duplication) of the first chromosome or chromosome segment.

[00245] In some embodiments, the value of f (such as the fetal fraction or tumor fraction) is used in the CNV determination, such as to compare the observed difference between the amount of two chromosomes or chromosome segments to the difference that would be expected for a particular type of CNV given the value of f (see, *e.g.*, US Publication No 2012/0190020; US Publication No 2012/0190021; US Publication No 2012/0190557; US Publication No

2012/0191358, which are each hereby incorporated by reference in its entirety). For example, the difference in the amount of a chromosome segment that is duplicated in a fetus compared to a disomic reference chromosome segment in a blood sample from a mother carrying the fetus increases as the fetal fraction increases. Additionally, the difference in the amount of a chromosome segment that is duplicated in a tumor compared to a disomic reference chromosome segment increases as the tumor fraction increases. In some embodiments, the method includes comparing the relative frequency of a chromosome or chromosome segment of interest to a reference chromosomes or chromosome segment (such as a chromosome or chromosome segment expected or known to be disomic) to the value of f to determine the likelihood of the CNV. For example, the difference in amounts between the first chromosomes or chromosome segment to the reference chromosome or chromosome segment can be compared to what would be expected given the value of f for various possible CNVs (such as one or two extra copies of a chromosome segment of interest).

Exemplary Reference Chromosomes or Chromosome Segments

[00246] In some embodiments, any of the methods described herein are also performed on one or more reference chromosomes or chromosomes segments and the results are compared to those for one or more chromosomes or chromosome segments of interest.

[00247] In some embodiments, the reference chromosome or chromosome segment is used as a control for what would be expected for the absence of a CNV. In some embodiments, the reference is the same chromosome or chromosome segment from one or more different samples known or expected to not have a deletion or duplication in that chromosome or chromosome segment. In some embodiments, the reference is a different chromosome or chromosome segment from the sample being tested that is expected to be disomic. In some embodiments, the reference is a different segment from one of the chromosomes of interest in the same sample that is being tested. For example, the reference may be one or more segments outside of the region of a potential deletion or duplication. Having a reference on the same chromosome that is being tested avoids variability between different chromosomes, such as differences in metabolism, apoptosis, histones, inactivation, and/or amplification between chromosomes. Analyzing segments without a CNV on the same chromosome as the one being tested can also be used to determine differences in metabolism, apoptosis, histones, inactivation, and/or amplification

between homologs, allowing the level of variability between homologs in the absence of a CNV to be determined for comparison to the results from a potential CNV. In some embodiments, the magnitude of the difference between the calculated and expected allele ratios for a potential CNV is greater than the corresponding magnitude for the reference, thereby confirming the presence of a CNV.

[00248] In some embodiments, the reference chromosome or chromosome segment is used as a control for what would be expected for the presence of a CNV, such as a particular deletion or duplication of interest. In some embodiments, the reference is the same chromosome or chromosome segment from one or more different samples known or expected to have a deletion or duplication in that chromosome or chromosome segment. In some embodiments, the reference is a different chromosome or chromosome segment from the sample being tested that is known or expected to have a CNV. In some embodiments, the magnitude of the difference between the calculated and expected allele ratios for a potential CNV is similar to (such as not significantly different) than the corresponding magnitude for the reference for the CNV, thereby confirming the presence of a CNV. In some embodiments, the magnitude of the difference between the calculated and expected allele ratios for a potential CNV is less than (such as significantly less) than the corresponding magnitude for the reference for the CNV, thereby confirming the absence of a CNV.

Exemplary Methods for Detecting a Phenotype

[00249] In some embodiments, the method includes analyzing a sample for a set of mutations associated with a disease or disorder (such as cancer) or an increased risk for a disease or disorder. There are strong correlations between events within classes (such as M or C cancer classes) which can be used to improve the signal to noise ratio of a method and classify tumors into distinct clinical subsets. For example, borderline results for a few mutations (such as a few CNVs) on one or more chromosomes or chromosomes segments considered jointly may be a very strong signal. In some embodiments, the correlation between events across multiple chromosomes is used to more powerfully look at a signal compared to looking at each of them individually. The design of the method itself can be optimized to best categorize tumors. This may be incredibly useful for early detection and screening--vis-a-vis recurrence where sensitivity to one particular mutation/CNV may be paramount. In some embodiments, the events are not

always correlated but have a probability of being correlated. In some embodiments, a matrix estimation formulation with a noise covariance matrix that has off diagonal terms is used.

[00250] In some embodiments, the invention features a method for detecting a phenotype (such as a cancer phenotype) in an individual, wherein the phenotype is defined by the presence of at least one of a set of mutations. In some embodiments, the method includes obtaining DNA or RNA measurements for a sample of DNA or RNA from one or more cells from the individual, wherein one or more of the cells is suspected of having the phenotype; and analyzing the DNA or RNA measurements to determine, for each of the mutations in the set of mutations, the likelihood that at least one of the cells has that mutation. In some embodiments, the method includes determining that the individual has the phenotype if either (i) for at least one of the mutations, the likelihood that at least one of the cells contains that mutations is greater than a threshold, or (ii) for at least one of the mutations, the likelihood that at least one of the cells has that mutations is less than the threshold, and for a plurality of the mutations, the combined likelihood that at least one of the cells has at least one of the mutations is greater than the threshold. In some embodiments, one or more cells have a subset or all of the mutations in the set of mutations. In some embodiments, the subset of mutations is associated with cancer or an increased risk for cancer. In some embodiments, the set of mutations includes a subset or all of the mutations in the M class of cancer mutations (Ciriello, Nat Genet. 45(10):1127-1133, 2013, doi: 10.1038/ng.2762, which is hereby incorporated by reference in its entirety). In some embodiments, the set of mutations includes a subset or all of the mutations in the C class of cancer mutations (Ciriello, *supra*). In some embodiments, the sample includes cell-free DNA or RNA. In some embodiments, the DNA or RNA measurements include measurements (such as the quantity of each allele at each locus) at a set of polymorphic loci on one or more chromosomes or chromosome segments of interest.

Exemplary Combinations of Methods

[00251] To increase the accuracy of the results, two or more methods (such as any of the methods of the invention or any known method) for detecting the presence or absence of a CNV are performed. In some embodiments, one or more methods for analyzing a factor (such as any of the method described herein or any known method) indicative of the presence or absence of a disease or disorder or an increased risk for a disease or disorder are performed.

[00252] In some embodiments, standard mathematical techniques are used to calculate the covariance and/or correlation between two or more methods. Standard mathematical techniques may also be used to determine the combined probability of a particular hypothesis based on two or more tests. Exemplary techniques include meta-analysis, Fisher's combined probability test for independent tests, Brown's method for combining dependent p-values with known covariance, and Kost's method for combining dependent p-values with unknown covariance. Exemplary methods of analyzing multiple factors or variables are disclosed in U.S. Patent No. 8,024,128 issued on September 20, 2011; U.S. Publication No. 2007/0027636, filed July 31, 2006; and U.S. Publication No. 2007/0178501, filed December 6, 2006, which are each hereby incorporated by reference in its entirety).

[00253] In various embodiments, the combined probability of a particular hypothesis or diagnosis is greater than 80, 85, 90, 92, 94, 96, 98, 99, or 99.9%, or is greater than some other threshold value.

Exemplary Samples

[00254] In some embodiments of any of the aspects of the invention, the sample includes cellular and/or extracellular genetic material from cells suspected of having a deletion or duplication, such as cells suspected of being cancerous. In some embodiments, the sample comprises any tissue or bodily fluid suspected of containing cells, DNA, or RNA having a deletion or duplication, such as cancer cells, DNA, or RNA. The genetic measurements used as part of these methods can be made on any sample comprising DNA or RNA, for example but not limited to, tissue, blood, serum, plasma, urine, hair, tears, saliva, skin, fingernails, feces, bile, lymph, cervical mucus, semen, or other cells or materials comprising nucleic acids. Samples may include any cell type or DNA or RNA from any cell type may be used (such as cells from any organ or tissue suspected of being cancerous, or neurons). In some embodiments, the sample includes nuclear and/or mitochondrial DNA. In some embodiments, the sample is from any of the target individuals disclosed herein. In some embodiments, the target individual is a born individual, a gestating fetus, a non-gestating fetus such as a products of conception sample, an embryo, or any other individual.

[00255] In some embodiments, the sample contains or is suspected to contain a mixture of DNA (or RNA), such as mixture of cancer DNA (or RNA) and noncancerous DNA (or RNA). In some embodiments, at least 0.5, 1, 3, 5, 7, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 92, 94, 95, 96, 98, 99, or 100% of the cells in the sample are cancer cells. In some embodiments, at least 0.5, 1, 3, 5, 7, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 92, 94, 95, 96, 98, 99, or 100% of the DNA (such as cfDNA) or RNA (such as cfRNA) in the sample is from cancer cell(s). In various embodiments, the percent of cells in the sample that are cancerous cells is between 0.5 to 99%, such as between 1 to 95%, 5 to 95%, 10 to 90%, 5 to 70%, 10 to 70%, 20 to 90%, or 20 to 70%, inclusive. In some embodiments, the sample is enriched for cancer cells or for DNA or RNA from cancer cells. In some embodiments in which the sample is enriched for cancer cells, at least 0.5, 1, 2, 3, 4, 5, 6, 7, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 92, 94, 95, 96, 98, 99, or 100% of the cells in the enriched sample are cancer cells. In some embodiments in which the sample is enriched for DNA or RNA from cancer cells, at least 0.5, 1, 2, 3, 4, 5, 6, 7, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 92, 94, 95, 96, 98, 99, or 100% of the DNA or RNA in the enriched sample is from cancer cell(s). In some embodiments, cell sorting (such as Fluorescent Activated Cell Sorting (FACS)) is used to enrich for cancer cells (Barteneva *et. al.*, Biochim Biophys Acta., 1836(1):105-22, Aug 2013. doi: 10.1016/j.bbcan.2013.02.004. Epub 2013 Feb 24, and Ibrahim *et al.*, Adv Biochem Eng Biotechnol. 106:19-39, 2007, which are each hereby incorporated by reference in its entirety).

[00256] In some embodiments of any of the aspects of the invention, the sample comprises any tissue suspected of being at least partially of fetal origin. In some embodiments, the sample includes cellular and/or extracellular genetic material from the fetus, contaminating cellular and/or extracellular genetic material (such as genetic material from the mother of the fetus), or combinations thereof. In some embodiments, the sample comprises cellular genetic material from the fetus, contaminating cellular genetic material, or combinations thereof.

[00257] In some embodiments, the sample is from a gestating fetus. In some embodiments, the sample is from a non-gestating fetus, such as a products of conception sample or a sample from any fetal tissue after fetal demise. In some embodiments, the sample is a maternal whole blood sample, cells isolated from a maternal blood sample, maternal plasma sample, maternal serum sample, amniocentesis sample, placental tissue sample (*e.g.*, chorionic villus, decidua, or

placental membrane), cervical mucus sample, or other sample from a fetus. In some embodiments, at least 3, 5, 7, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 92, 94, 95, 96, 98, 99, or 100% of the cells in the sample are maternal cells. In various embodiments, the percent of cells in the sample that are maternal cells is between 5 to 99%, such as between 10 to 95%, 20 to 95%, 30 to 90%, 30 to 70%, 40 to 90%, 40 to 70%, 50 to 90%, or 50 to 80%, inclusive.

[00258] In some embodiments, the sample is enriched for fetal cells. In some embodiments in which the sample is enriched for fetal cells, at least 0.5, 1, 2, 3, 4, 5, 6, 7% or more of the cells in the enriched sample are fetal cells. In some embodiments, the percent of cells in the sample that are fetal cells is between 0.5 to 100%, such as between 1 to 99%, 5 to 95%, 10 to 95%, 10 to 95%, 20 to 90%, or 30 to 70%, inclusive. In some embodiments, the sample is enriched for fetal DNA. In some embodiments in which the sample is enriched for fetal DNA, at least 0.5, 1, 2, 3, 4, 5, 6, 7% or more of the DNA in the enriched sample is fetal DNA. In some embodiments, the percent of DNA in the sample that is fetal DNA is between 0.5 to 100%, such as between 1 to 99%, 5 to 95%, 10 to 95%, 10 to 95%, 20 to 90%, or 30 to 70%, inclusive.

[00259] In some embodiments, the sample includes a single cell or includes DNA and/or RNA from a single cell. In some embodiments, multiple individual cells (*e.g.*, at least 5, 10, 20, 30, 40, or 50 cells from the same subject or from different subjects) are analyzed in parallel. In some embodiments, cells from multiple samples from the same individual are combined, which reduces the amount of work compared to analyzing the samples separately. Combining multiple samples can also allow multiple tissues to be tested for cancer simultaneously (which can be used to provide or more thorough screening for cancer or to determine whether cancer may have metastasized to other tissues).

[00260] In some embodiments, the sample contains a single cell or a small number of cells, such as 2, 3, 5, 6, 7, 8, 9, or 10 cells. In some embodiments, the sample has between 1 to 100, 100 to 500, or 500 to 1,000 cells, inclusive. In some embodiments, the sample contains 1 to 10 picograms, 10 to 100 picograms, 100 picograms to 1 nanogram, 1 to 10 nanograms, 10 to 100 nanograms, or 100 nanograms to 1 microgram of RNA and/or DNA, inclusive.

[00261] In some embodiments, the sample is embedded in paraffin. In some embodiments, the sample is preserved with a preservative such as formaldehyde and optionally encased in paraffin, which may cause cross-linking of the DNA such that less of it is available for PCR. In

some embodiments, the sample is a fresh sample (such as a sample obtained with 1 or 2 days of analysis). In some embodiments, the sample is frozen prior to analysis. In some embodiments, the sample is a historical sample.

[00262] These samples can be used in any of the methods of the invention.

Exemplary Sample Analysis Methods

[00263] In some embodiments, the method includes isolating or purifying the DNA and/or RNA. There are a number of standard procedures known in the art to accomplish such an end. In some embodiments, the sample may be centrifuged to separate various layers. In some embodiments, the DNA or RNA may be isolated using filtration. In some embodiments, the preparation of the DNA or RNA may involve amplification, separation, purification by chromatography, liquid liquid separation, isolation, preferential enrichment, preferential amplification, targeted amplification, or any of a number of other techniques either known in the art or described herein. In some embodiments for the isolation of DNA, RNase is used to degrade RNA. In some embodiments for the isolation of RNA, DNase (such as DNase I from Invitrogen, Carlsbad, CA, USA) is used to degrade DNA. In some embodiments, an RNeasy mini kit (Qiagen), is used to isolate RNA according to the manufacturer's protocol. In some embodiments, small RNA molecules are isolated using the mirVana PARIS kit (Ambion, Austin, TX, USA) according to the manufacturer's protocol (Gu *et al.*, J. Neurochem. 122:641–649, 2012, , which is hereby incorporated by reference in its entirety). The concentration and purity of RNA may optionally be determined using Nanovue (GE Healthcare, Piscataway, NJ, USA), and RNA integrity may optionally be measured by use of the 2100 Bioanalyzer (Agilent Technologies, Santa Clara, CA, USA) (Gu *et al.*, J. Neurochem. 122:641–649, 2012, , which is hereby incorporated by reference in its entirety). In some embodiments, TRIZOL or RNAlater (Ambion) is used to stabilize RNA during storage.

[00264] In some embodiments, universal tagged adaptors are added to make a library. Prior to ligation, sample DNA may be blunt ended, and then a single adenosine base is added to the 3-prime end. Prior to ligation the DNA may be cleaved using a restriction enzyme or some other cleavage method. During ligation the 3-prime adenosine of the sample fragments and the complementary 3-prime tyrosine overhang of adaptor can enhance ligation efficiency. In some

embodiments, adaptor ligation is performed using the ligation kit found in the AGILENT SURESELECT kit. In some embodiments, the library is amplified using universal primers. In an embodiment, the amplified library is fractionated by size separation or by using products such as AGENCOURT AMPURE beads or other similar methods. In some embodiments, PCR amplification is used to amplify target loci. In some embodiments, the amplified DNA is sequenced (such as sequencing using an ILLUMINA IIGAX or HiSeq sequencer). In some embodiments, the amplified DNA is sequenced from each end of the amplified DNA to reduce sequencing errors. If there is a sequence error in a particular base when sequencing from one end of the amplified DNA, there is less likely to be a sequence error in the complementary base when sequencing from the other side of the amplified DNA (compared to sequencing multiple times from the same end of the amplified DNA).

[00265] In some embodiments, whole genome application (WGA) is used to amplify a nucleic acid sample. There are a number of methods available for WGA: ligation-mediated PCR (LM-PCR), degenerate oligonucleotide primer PCR (DOP-PCR), and multiple displacement amplification (MDA). In LM-PCR, short DNA sequences called adapters are ligated to blunt ends of DNA. These adapters contain universal amplification sequences, which are used to amplify the DNA by PCR. In DOP-PCR, random primers that also contain universal amplification sequences are used in a first round of annealing and PCR. Then, a second round of PCR is used to amplify the sequences further with the universal primer sequences. MDA uses the phi-29 polymerase, which is a highly processive and non-specific enzyme that replicates DNA and has been used for single-cell analysis. In some embodiments, WGA is not performed.

[00266] In some embodiments, selective amplification or enrichment are used to amplify or enrich target loci. In some embodiments, the amplification and/or selective enrichment technique may involve PCR such as ligation mediated PCR, fragment capture by hybridization, Molecular Inversion Probes, or other circularizing probes. In some embodiments, real-time quantitative PCR (RT-qPCR), digital PCR, or emulsion PCR, single allele base extension reaction followed by mass spectrometry are used (Hung et al., J Clin Pathol 62:308–313, 2009, which is hereby incorporated by reference in its entirety). In some embodiments, capture by hybridization with hybrid capture probes is used to preferentially enrich the DNA. In some

embodiments, methods for amplification or selective enrichment may involve using probes where, upon correct hybridization to the target sequence, the 3-prime end or 5-prime end of a nucleotide probe is separated from the polymorphic site of a polymorphic allele by a small number of nucleotides. This separation reduces preferential amplification of one allele, termed allele bias. This is an improvement over methods that involve using probes where the 3-prime end or 5-prime end of a correctly hybridized probe are directly adjacent to or very near to the polymorphic site of an allele. In an embodiment, probes in which the hybridizing region may or certainly contains a polymorphic site are excluded. Polymorphic sites at the site of hybridization can cause unequal hybridization or inhibit hybridization altogether in some alleles, resulting in preferential amplification of certain alleles. These embodiments are improvements over other methods that involve targeted amplification and/or selective enrichment in that they better preserve the original allele frequencies of the sample at each polymorphic locus, whether the sample is pure genomic sample from a single individual or mixture of individuals

[00267] In some embodiments, PCR (referred to as mini-PCR) is used to generate very short amplicons (US Application No. 13/683,604, filed Nov. 21, 2012, U.S. Publication No. 2013/0123120, and U.S. Application No. 13/300,235, filed Nov. 18, 2011, U.S. Publication No. 2012/0270212, filed Nov. 18, 2011 which are each hereby incorporated by reference in its entirety). cfDNA (such as fetal cfDNA in maternal serum or necroptically- or apoptotically-released cancer cfDNA) is highly fragmented. For fetal cfDNA, the fragment sizes are distributed in approximately a Gaussian fashion with a mean of 160 bp, a standard deviation of 15 bp, a minimum size of about 100 bp, and a maximum size of about 220 bp. The polymorphic site of one particular target locus may occupy any position from the start to the end among the various fragments originating from that locus. Because cfDNA fragments are short, the likelihood of both primer sites being present the likelihood of a fragment of length L comprising both the forward and reverse primers sites is ratio of the length of the amplicon to the length of the fragment. Under ideal conditions, assays in which the amplicon is 45, 50, 55, 60, 65, or 70 bp will successfully amplify from 72%, 69%, 66%, 63%, 59%, or 56%, respectively, of available template fragment molecules. The amplicon length is the distance between the 5-prime ends of the forward and reverse priming sites. Amplicon length that is shorter than typically used by those known in the art may result in more efficient measurements of the desired polymorphic

loci by only requiring short sequence reads. In an embodiment, a substantial fraction of the amplicons are less than 100 bp, less than 90 bp, less than 80 bp, less than 70 bp, less than 65 bp, less than 60 bp, less than 55 bp, less than 50 bp, or less than 45 bp.

[00268] In some embodiments, amplification is performed using direct multiplexed PCR, sequential *PCR*, nested PCR, doubly nested PCR, one-and-a-half sided nested PCR, fully nested PCR, one sided fully nested PCR, one-sided nested PCR, hemi-nested PCR, hemi-nested PCR, triply hemi-nested PCR, semi-nested PCR, one sided semi-nested PCR, reverse semi-nested PCR method, or one-sided PCR, which are described in US Application No. 13/683,604, filed Nov. 21, 2012, U.S. Publication No. 2013/0123120, and U.S. Application No. 13/300,235, filed Nov. 18, 2011, U.S. Publication No. 2012/0270212, which are hereby incorporated by reference in their entirety. If desired, any of these methods can be used for mini-PCR.

[00269] If desired, the extension step of the PCR amplification may be limited from a time standpoint to reduce amplification from fragments longer than 200 nucleotides, 300 nucleotides, 400 nucleotides, 500 nucleotides or 1,000 nucleotides. This may result in the enrichment of fragmented or shorter DNA (such as fetal DNA or DNA from cancer cells that have undergone apoptosis or necrosis) and improvement of test performance.

[00270] In some embodiments, multiplex PCR is used. In some embodiments, the method of amplifying target loci in a nucleic acid sample involves (i) contacting the nucleic acid sample with a library of primers that simultaneously hybridize to least 100; 200; 500; 750; 1,000; 2,000; 5,000; 7,500; 10,000; 20,000; 25,000; 30,000; 40,000; 50,000; 75,000; or 100,000 different target loci to produce a reaction mixture; and (ii) subjecting the reaction mixture to primer extension reaction conditions (such as PCR conditions) to produce amplified products that include target amplicons. In some embodiments, at least 50, 60, 70, 80, 90, 95, 96, 97, 98, 99, or 99.5% of the targeted loci are amplified. In various embodiments, less than 60, 50, 40, 30, 20, 10, 5, 4, 3, 2, 1, 0.5, 0.25, 0.1, or 0.05% of the amplified products are primer dimers. In some embodiments, the primers are in solution (such as being dissolved in the liquid phase rather than in a solid phase). In some embodiments, the primers are in solution and are not immobilized on a solid support. In some embodiments, the primers are not part of a microarray. In some embodiments, the primers do not include molecular inversion probes (MIPs).

[00271] The selective enrichment and/or amplification may involve tagging each individual molecule with different tags, molecular barcodes, tags for amplification, and/or tags for sequencing. In some embodiments, the amplified products are analyzed by sequencing or by hybridization to an array, such as a SNP array, the ILLUMINA INFINIUM array, or the AFFYMETRIX gene chip.

[00272] Additional exemplary sample preparation, amplification, and quantification methods are described in US Application No. 13/683,604, filed Nov. 21, 2012 (U.S. Publication No. 2013/0123120, which is hereby incorporated by reference in its entirety). These methods can be used for analysis of any of the samples disclosed herein.

Exemplary Quantification Methods for Cell-free DNA

[00273] If desired, that amount or concentration of cfDNA or cfRNA can be measured using standard methods. In some embodiments, the amount or concentration of cell-free mitochondrial DNA (cf mDNA) is determined. In some embodiments, the amount or concentration of cell-free DNA that originated from nuclear DNA (cf nDNA) is determined. In some embodiments, the amount or concentration of cf mDNA and cf nDNA are determined simultaneously.

[00274] In some embodiments, qPCR is used to measure cf nDNA and/or cf mDNA (Kohler *et al.* "Levels of plasma circulating cell free nuclear and mitochondrial DNA as potential biomarkers for breast tumors." Mol Cancer 8:105, 2009, 8:doi:10.1186/1476-4598-8-105, which is hereby incorporated by reference in its entirety). For example, one or more loci from cf nDNA (such as Glyceraldehyd-3-phosphat-dehydrogenase, *GAPDH*) and one or more loci from cf mDNA (ATPase 8, *MTATP 8*) can be measured using multiplex qPCR. In some embodiments, fluorescence-labelled PCR is used to measure cf nDNA and/or cf mDNA (Schwarzenbach *et al.*, "Evaluation of cell-free tumour DNA and RNA in patients with breast cancer and benign breast disease." Mol Biosys 7:2848-2854, 2011, which is hereby incorporated by reference in its entirety). If desired, the normality distribution of the data can be determined using standard methods, such as the Shapiro-Wilk-Test. If desired, cf nDNA and mDNA levels can be compared using standard methods, such as the Mann-Whitney-U-Test. In some embodiments, cf nDNA and/or mDNA levels are compared with other established prognostic factors using standard methods, such as the Mann-Whitney-U-Test or the Kruskal-Wallis-Test

Exemplary RNA Amplification, Quantification, and Analysis Methods

[00275] Any of the following exemplary methods may be used to amplify and optionally quantify RNA, such as such as cfRNA, cellular RNA, cytoplasmic RNA, coding cytoplasmic RNA, non-coding cytoplasmic RNA, mRNA, miRNA, mitochondrial RNA, rRNA, or tRNA. In some embodiments, the miRNA is any of the miRNA molecules listed in the miRBase database available at the world wide web at mirbase.org. Exemplary miRNA molecules include miR-509; miR-21, and miR-146a.

[00276] In some embodiments, reverse-transcriptase multiplex ligation-dependent probe amplification (RT-MLPA) is used to amplify RNA. In some embodiments, each set of hybridizing probes consists of two short synthetic oligonucleotides spanning the SNP and one long oligonucleotide (Li *et al.*, Arch Gynecol Obstet. “Development of noninvasive prenatal diagnosis of trisomy 21 by RT-MLPA with a new set of SNP markers,” July 5, 2013, DOI 10.1007/s00404-013-2926-5; Schouten *et al.* “Relative quantification of 40 nucleic acid sequences by multiplex ligation- dependent probe amplification.” Nucleic Acids Res 30:e57, 2002; Deng et al. (2011) “Non-invasive prenatal diagnosis of trisomy 21 by reverse transcriptase multiplex ligation-dependent probe amplification,” Clin, Chem. Lab Med. 49:641–646, 2011, which are each hereby incorporated by reference in its entirety).

[00277] In some embodiments, RNA is amplified with reverse-transcriptase PCR. In some embodiments, RNA is amplified with real-time reverse-transcriptase PCR, such as one-step real-time reverse-transcriptase PCR with SYBR GREEN I as previously described (Li *et al.*, Arch Gynecol Obstet. “Development of noninvasive prenatal diagnosis of trisomy 21 by RT-MLPA with a new set of SNP markers,” July 5, 2013, DOI 10.1007/s00404-013-2926-5; Lo et al., “Plasma placental RNA allelic ratio permits noninvasive prenatal chromosomal aneuploidy detection,” Nat Med 13:218–223, 2007; Tsui et al., Systematic micro-array based identification of placental mRNA in maternal plasma: towards non-invasive prenatal gene expression profiling. J Med Genet 41:461–467, 2004; Gu *et al.*, J. Neurochem. 122:641–649, 2012, which are each hereby incorporated by reference in its entirety).

[00278] In some embodiments, a microarray is used to detect RNA. For example, a human miRNA microarray from Agilent Technologies can be used according to the manufacturer’s protocol. Briefly, isolated RNA is dephosphorylated and ligated with pCp-Cy3. Labeled RNA is purified and hybridized to miRNA arrays containing probes for human mature miRNAs on the

basis of Sanger miRBase release 14.0. The arrays is washed and scanned with use of a microarray scanner (G2565BA, Agilent Technologies). The intensity of each hybridization signal is evaluated by Agilent extraction software v9.5.3. The labeling, hybridization, and scanning may be performed according to the protocols in the Agilent miRNA microarray system (Gu *et al.*, J. Neurochem. 122:641–649, 2012, which is hereby incorporated by reference in its entirety).

[00279] In some embodiments, a TaqMan assay is used to detect RNA. An exemplary assay is the TaqMan Array Human MicroRNA Panel v1.0 (Early Access) (Applied Biosystems), which contains 157 TaqMan MicroRNA Assays, including the respective reverse-transcription primers, PCR primers, and TaqMan probe (Chim *et al.*, “Detection and characterization of placental microRNAs in maternal plasma,” Clin Chem. 54(3):482-90, 2008, which is hereby incorporated by reference in its entirety).

[00280] If desired, the mRNA splicing pattern of one or more mRNAs can be determined using standard methods (Fackenthal1 and Godley, Disease Models & Mechanisms 1: 37-42, 2008, doi:10.1242/dmm.000331, which is hereby incorporated by reference in its entirety). For example, high-density microarrays and/or high-throughput DNA sequencing can be used to detect mRNA splice variants.

Exemplary Amplification Methods

[00281] Improved PCR amplification methods have also been developed that minimize or prevent interference due to the amplification of nearby or adjacent target loci in the same reaction volume (such as part of the sample multiplex PCR reaction that simultaneously amplifies all the target loci). These methods can be used to simultaneously amplify nearby or adjacent target loci, which is faster and cheaper than having to separate nearby target loci into different reaction volumes so that they can be amplified separately to avoid interference. In particular embodiments, these methods are used to tile a region such that the amplicons include all the nucleotides in the region (such as an exon or all the exons of a gene such as cystic fibrosis).

[00282] In some embodiments, the amplification of target loci is performed using a polymerase (*e.g.*, a DNA polymerase, RNA polymerase, or reverse transcriptase) with low 5'→3' exonuclease and/or low strand displacement activity. In some embodiments, the low level of

5'→3' exonuclease reduces or prevents the degradation of a nearby primer (*e.g.*, an unextended primer or a primer that has had one or more nucleotides added to during primer extension). In some embodiments, the low level of strand displacement activity reduces or prevents the displacement of a nearby primer (*e.g.*, an unextended primer or a primer that has had one or more nucleotides added to it during primer extension). In some embodiments, target loci that are adjacent to each other (*e.g.*, no bases between the target loci) or nearby (*e.g.*, loci are within 50, 40, 30, 20, 15, 10, 9, 8, 7, 6, 5, 4, 3, 2, or 1 base) are amplified. In some embodiments, the 3' end of one locus is within 50, 40, 30, 20, 15, 10, 9, 8, 7, 6, 5, 4, 3, 2, or 1 base of the 5' end of next downstream locus.

[00283] In some embodiments, at least 100, 200, 500, 750, 1,000; 2,000; 5,000; 7,500; 10,000; 20,000; 25,000; 30,000; 40,000; 50,000; 75,000; or 100,000 different target loci are amplified, such as by the simultaneous amplification in one reaction volume. In some embodiments, at least 50, 60, 70, 80, 90, 95, 96, 97, 98, 99, or 99.5% of the amplified products are target amplicons. In various embodiments, the amount of amplified products that are target amplicons is between 50 to 99.5%, such as between 60 to 99%, 70 to 98%, 80 to 98%, 90 to 99.5%, or 95 to 99.5%, inclusive. In some embodiments, at least 50, 60, 70, 80, 90, 95, 96, 97, 98, 99, or 99.5% of the targeted loci are amplified (*e.g.*, amplified at least 5, 10, 20, 30, 50, or 100-fold compared to the amount prior to amplification), such as by the simultaneous amplification in one reaction volume. In various embodiments, the amount target loci that are amplified (*e.g.*, amplified at least 5, 10, 20, 30, 50, or 100-fold compared to the amount prior to amplification) is between 50 to 99.5%, such as between 60 to 99%, 70 to 98%, 80 to 99%, 90 to 99.5%, 95 to 99.9%, or 98 to 99.99% inclusive. In some embodiments, fewer non-target amplicons are produced, such as fewer amplicons formed from a forward primer from a first primer pair and a reverse primer from a second primer pair. Such undesired non-target amplicons can be produced using prior amplification methods if, *e.g.*, the reverse primer from the first primer pair and/or the forward primer from the second primer pair are degraded and/or displaced.

[00284] In some embodiments, these methods allows longer extension times to be used since the polymerase bound to a primer being extended is less likely to degrade and/or displace a nearby primer (such as the next downstream primer) given the low 5'→3' exonuclease and/or low strand displacement activity of the polymerase. In various embodiments, reaction conditions (such as the extension time and temperature) are used such that the extension rate of the

polymerase allows the number of nucleotides that are added to a primer being extended to be equal to or greater than 80, 90, 95, 100, 110, 120, 130, 140, 150, 175, or 200% of the number of nucleotides between the 3' end of the primer binding site and the 5' end of the next downstream primer binding site on the same strand.

[00285] In some embodiments, a DNA polymerase is used produce DNA amplicons using DNA as a template. In some embodiments, a RNA polymerase is used produce RNA amplicons using DNA as a template. In some embodiments, a reverse transcriptase is used produce cDNA amplicons using RNA as a template.

[00286] In some embodiments, the low level of 5'→3' exonuclease of the polymerase is less than 80, 70, 60, 50, 40, 30, 20, 10, 5, 1, or 0.1% of the activity of the same amount of *Thermus aquaticus* polymerase ("Taq" polymerase, which is a commonly used DNA polymerase from a thermophilic bacterium, PDB 1BGX, EC 2.7.7.7, Murali *et al.*, "Crystal structure of Taq DNA polymerase in complex with an inhibitory Fab: the Fab is directed against an intermediate in the helix-coil dynamics of the enzyme," Proc. Natl. Acad. Sci. USA 95:12562-12567, 1998, which is hereby incorporated by reference in its entirety) under the same conditions. In some embodiments, the low level of strand displacement activity of the polymerase is less than 80, 70, 60, 50, 40, 30, 20, 10, 5, 1, or 0.1% of the activity of the same amount of Taq polymerase under the same conditions.

[00287] In some embodiments, the polymerase is a PUSHION DNA polymerase, such as PHUSION High Fidelity DNA polymerase (M0530S, New England BioLabs, Inc.) or PHUSION Hot Start Flex DNA polymerase (M0535S, New England BioLabs, Inc.; Frey and Suppmann *BioChemica*. 2:34-35, 1995; Chester and Marshak *Analytical Biochemistry*. 209:284-290, 1993, which are each hereby incorporated by reference in its entirety). The PHUSION DNA polymerase is a *Pyrococcus*-like enzyme fused with a processivity-enhancing domain. PHUSION DNA polymerase possesses 5'→3' polymerase activity and 3'→5' exonuclease activity, and generates blunt-ended products. PHUSION DNA polymerase lacks 5'→3' exonuclease activity and strand displacement activity.

[00288] In some embodiments, the polymerase is a Q5® DNA Polymerase, such as Q5® High-Fidelity DNA Polymerase (M0491S, New England BioLabs, Inc.) or Q5® Hot Start High-Fidelity DNA Polymerase (M0493S, New England BioLabs, Inc.). Q5® High-Fidelity DNA polymerase is a high-fidelity, thermostable, DNA polymerase with 3'→5' exonuclease activity,

fused to a processivity-enhancing Sso7d domain. Q5® High-Fidelity DNA polymerase lacks 5'→3' exonuclease activity and strand displacement activity.

[00289] In some embodiments, the polymerase is a T4 DNA polymerase (M0203S, New England BioLabs, Inc.; Tabor and Struh. (1989). “DNA-Dependent DNA Polymerases,” In Ausebel et al. (Ed.), *Current Protocols in Molecular Biology*. 3.5.10-3.5.12. New York: John Wiley & Sons, Inc., 1989; Sambrook et al. *Molecular Cloning: A Laboratory Manual*. (2nd ed.), 5.44-5.47. Cold Spring Harbor: Cold Spring Harbor Laboratory Press, 1989, which are each hereby incorporated by reference in its entirety). T4 DNA Polymerase catalyzes the synthesis of DNA in the 5'→3' direction and requires the presence of template and primer. This enzyme has a 3'→5' exonuclease activity which is much more active than that found in DNA Polymerase I. T4 DNA polymerase lacks 5'→3' exonuclease activity and strand displacement activity.

[00290] In some embodiments, the polymerase is a *Sulfolobus* DNA Polymerase IV (M0327S, New England BioLabs, Inc.; (Boudsocq, et al. (2001). *Nucleic Acids Res.*, 29:4607-4616, 2001; McDonald, et al. (2006). *Nucleic Acids Res.*, 34:1102-1111, 2006, which are each hereby incorporated by reference in its entirety). *Sulfolobus* DNA Polymerase IV is a thermostable Y-family lesion-bypass DNA Polymerase that efficiently synthesizes DNA across a variety of DNA template lesions McDonald, J.P. et al. (2006). *Nucleic Acids Res.*, 34, 1102-1111, which is hereby incorporated by reference in its entirety). *Sulfolobus* DNA Polymerase IV lacks 5'→3' exonuclease activity and strand displacement activity.

[00291] In some embodiments, if a primer binds a region with a SNP, the primer may bind and amplify the different alleles with different efficiencies or may only bind and amplify one allele. For subjects who are heterozygous, one of the alleles may not be amplified by the primer. In some embodiments, a primer is designed for each allele. For example, if there are two alleles (e.g., a biallelic SNP), then two primers can be used to bind the same location of a target locus (e.g., a forward primer to bind the “A” allele and a forward primer to bind the “B” allele). Standard methods, such as the dbSNP database, can be used to determine the location of known SNPs, such as SNP hot spots that have a high heterozygosity rate.

[00292] In some embodiments, the amplicons are similar in size. In some embodiments, the range of the length of the target amplicons is less than 100, 75, 50, 25, 15, 10, or 5 nucleotides. In some embodiments (such as the amplification of target loci in fragmented DNA or RNA), the length of the target amplicons is between 50 and 100 nucleotides, such as between 60 and 80

nucleotides, or 60 and 75 nucleotides, inclusive. In some embodiments (such as the amplification of multiple target loci throughout an exon or gene), the length of the target amplicons is between 100 and 500 nucleotides, such as between 150 and 450 nucleotides, 200 and 400 nucleotides, 200 and 300 nucleotides, or 300 and 400 nucleotides, inclusive.

[00293] In some embodiments, multiple target loci are simultaneously amplified using a primer pair that includes a forward and reverse primer for each target locus to be amplified in that reaction volume. In some embodiments, one round of PCR is performed with a single primer per target locus, and then a second round of PCR is performed with a primer pair per target locus. For example, the first round of PCR may be performed with a single primer per target locus such that all the primers bind the same strand (such as using a forward primer for each target locus). This allows the PCR to amplify in a linear manner and reduces or eliminates amplification bias between amplicons due to sequence or length differences. In some embodiments, the amplicons are then amplified using a forward and reverse primer for each target locus.

Exemplary Primer Design Methods

[00294] If desired, multiplex PCR may be performed using primers with a decreased likelihood of forming primer dimers. In particular, highly multiplexed PCR can often result in the production of a very high proportion of product DNA that results from unproductive side reactions such as primer dimer formation. In an embodiment, the particular primers that are most likely to cause unproductive side reactions may be removed from the primer library to give a primer library that will result in a greater proportion of amplified DNA that maps to the genome. The step of removing problematic primers, that is, those primers that are particularly likely to form dimers has unexpectedly enabled extremely high PCR multiplexing levels for subsequent analysis by sequencing.

[00295] There are a number of ways to choose primers for a library where the amount of non-mapping primer dimer or other primer mischief products are minimized. Empirical data indicate that a small number of ‘bad’ primers are responsible for a large amount of non-mapping primer dimer side reactions. Removing these ‘bad’ primers can increase the percent of sequence reads that map to targeted loci. One way to identify the ‘bad’ primers is to look at the sequencing data of DNA that was amplified by targeted amplification; those primer dimers that are seen with greatest frequency can be removed to give a primer library that is significantly less likely to

result in side product DNA that does not map to the genome. There are also publicly available programs that can calculate the binding energy of various primer combinations, and removing those with the highest binding energy will also give a primer library that is significantly less likely to result in side product DNA that does not map to the genome.

[00296] In some embodiments for selecting primers, an initial library of candidate primers is created by designing one or more primers or primer pairs to candidate target loci. A set of candidate target loci (such as SNPs) can be selected based on publically available information about desired parameters for the target loci, such as frequency of the SNPs within a target population or the heterozygosity rate of the SNPs. In one embodiment, the PCR primers may be designed using the Primer3 program (the worldwide web at primer3.sourceforge.net; libprimer3 release 2.2.3, which is hereby incorporated by reference in its entirety). If desired, the primers can be designed to anneal within a particular annealing temperature range, have a particular range of GC contents, have a particular size range, produce target amplicons in a particular size range, and/or have other parameter characteristics. Starting with multiple primers or primer pairs per candidate target locus increases the likelihood that a primer or primer pair will remain in the library for most or all of the target loci. In one embodiment, the selection criteria may require that at least one primer pair per target locus remains in the library. That way, most or all of the target loci will be amplified when using the final primer library. This is desirable for applications such as screening for deletions or duplications at a large number of locations in the genome or screening for a large number of sequences (such as polymorphisms or other mutations) associated with a disease or an increased risk for a disease. If a primer pair from the library would produce a target amplicon that overlaps with a target amplicon produced by another primer pair, one of the primer pairs may be removed from the library to prevent interference.

[00297] In some embodiments, an “undesirability score” (higher score representing least desirability) is calculated (such as calculation on a computer) for most or all of the possible combinations of two primers from a library of candidate primers. In various embodiments, an undesirability score is calculated for at least 80, 90, 95, 98, 99, or 99.5% of the possible combinations of candidate primers in the library. Each undesirability score is based at least in part on the likelihood of dimer formation between the two candidate primers. If desired, the undesirability score may also be based on one or more other parameters selected from the group

consisting of heterozygosity rate of the target locus, disease prevalence associated with a sequence (*e.g.*, a polymorphism) at the target locus, disease penetrance associated with a sequence (*e.g.*, a polymorphism) at the target locus, specificity of the candidate primer for the target locus, size of the candidate primer, melting temperature of the target amplicon, GC content of the target amplicon, amplification efficiency of the target amplicon, and size of the target amplicon. In some embodiments, the specificity of the candidate primer for the target locus includes the likelihood that the candidate primer will mis-prime by binding and amplifying a locus other than the target locus it was designed to amplify. In some embodiments, one or more or all the candidate primers that mis-prime are removed from the library. In some embodiments to increase the number of candidate primers to choose from, candidate primers that may mis-prime are not removed from the library. If multiple factors are considered, the undesirability score may be calculated based on a weighted average of the various parameters. The parameters may be assigned different weights based on their importance for the particular application that the primers will be used for. In some embodiments, the primer with the highest undesirability score is removed from the library. If the removed primer is a member of a primer pair that hybridizes to one target locus, then the other member of the primer pair may be removed from the library. The process of removing primers may be repeated as desired. In some embodiments, the selection method is performed until the undesirability scores for the candidate primer combinations remaining in the library are all equal to or below a minimum threshold. In some embodiments, the selection method is performed until the number of candidate primers remaining in the library is reduced to a desired number.

[00298] In various embodiments, after the undesirability scores are calculated, the candidate primer that is part of the greatest number of combinations of two candidate primers with an undesirability score above a first minimum threshold is removed from the library. This step ignores interactions equal to or below the first minimum threshold since these interactions are less significant. If the removed primer is a member of a primer pair that hybridizes to one target locus, then the other member of the primer pair may be removed from the library. The process of removing primers may be repeated as desired. In some embodiments, the selection method is performed until the undesirability scores for the candidate primer combinations remaining in the library are all equal to or below the first minimum threshold. If the number of candidate primers remaining in the library is higher than desired, the number of primers may be reduced by

decreasing the first minimum threshold to a lower second minimum threshold and repeating the process of removing primers. If the number of candidate primers remaining in the library is lower than desired, the method can be continued by increasing the first minimum threshold to a higher second minimum threshold and repeating the process of removing primers using the original candidate primer library, thereby allowing more of the candidate primers to remain in the library. In some embodiments, the selection method is performed until the undesirability scores for the candidate primer combinations remaining in the library are all equal to or below the second minimum threshold, or until the number of candidate primers remaining in the library is reduced to a desired number. ,

[00299] If desired, primer pairs that produce a target amplicon that overlaps with a target amplicon produced by another primer pair can be divided into separate amplification reactions. Multiple PCR amplification reactions may be desirable for applications in which it is desirable to analyze all of the candidate target loci (instead of omitting candidate target loci from the analysis due to overlapping target amplicons).

[00300] These selection methods minimize the number of candidate primers that have to be removed from the library to achieve the desired reduction in primer dimers. By removing a smaller number of candidate primers from the library, more (or all) of the target loci can be amplified using the resulting primer library.

[00301] Multiplexing large numbers of primers imposes considerable constraint on the assays that can be included. Assays that unintentionally interact result in spurious amplification products. The size constraints of miniPCR may result in further constraints. In an embodiment, it is possible to begin with a very large number of potential SNP targets (between about 500 to greater than 1 million) and attempt to design primers to amplify each SNP. Where primers can be designed it is possible to attempt to identify primer pairs likely to form spurious products by evaluating the likelihood of spurious primer duplex formation between all possible pairs of primers using published thermodynamic parameters for DNA duplex formation. Primer interactions may be ranked by a scoring function related to the interaction and primers with the worst interaction scores are eliminated until the number of primers desired is met. In cases where SNPs likely to be heterozygous are most useful, it is possible to also rank the list of assays and select the most heterozygous compatible assays. Experiments have validated that primers with high interaction scores are most likely to form primer dimers. At high multiplexing it is not

possible to eliminate all spurious interactions, but it is essential to remove the primers or pairs of primers with the highest interaction scores *in silico* as they can dominate an entire reaction, greatly limiting amplification from intended targets. We have performed this procedure to create multiplex primer sets of up to and in some cases more than 10,000 primers. The improvement due to this procedure is substantial, enabling amplification of more than 80%, more than 90%, more than 95%, more than 98%, and even more than 99% on target products as determined by sequencing of all PCR products, as compared to 10% from a reaction in which the worst primers were not removed. When combined with a partial semi-nested approach as previously described, more than 90%, and even more than 95% of amplicons may map to the targeted sequences.

[00302] Note that there are other methods for determining which PCR probes are likely to form dimers. In an embodiment, analysis of a pool of DNA that has been amplified using a non-optimized set of primers may be sufficient to determine problematic primers. For example, analysis may be done using sequencing, and those dimers which are present in the greatest number are determined to be those most likely to form dimers, and may be removed. In an embodiment, the method of primer design may be used in combination with the mini-PCR method described herein.

[00303] The use of tags on the primers may reduce amplification and sequencing of primer dimer products. In some embodiments, the primer contains an internal region that forms a loop structure with a tag. In particular embodiments, the primers include a 5' region that is specific for a target locus, an internal region that is not specific for the target locus and forms a loop structure, and a 3' region that is specific for the target locus. In some embodiments, the loop region may lie between two binding regions where the two binding regions are designed to bind to contiguous or neighboring regions of template DNA. In various embodiments, the length of the 3' region is at least 7 nucleotides. In some embodiments, the length of the 3' region is between 7 and 20 nucleotides, such as between 7 to 15 nucleotides, or 7 to 10 nucleotides, inclusive. In various embodiments, the primers include a 5' region that is not specific for a target locus (such as a tag or a universal primer binding site) followed by a region that is specific for a target locus, an internal region that is not specific for the target locus and forms a loop structure, and a 3' region that is specific for the target locus. Tag-primers can be used to shorten necessary target-specific sequences to below 20, below 15, below 12, and even below 10 base pairs. This can be serendipitous with standard primer design when the target sequence is

fragmented within the primer binding site or, or it can be designed into the primer design. Advantages of this method include: it increases the number of assays that can be designed for a certain maximal amplicon length, and it shortens the “non-informative” sequencing of primer sequence. It may also be used in combination with internal tagging.

[00304] In an embodiment, the relative amount of nonproductive products in the multiplexed targeted PCR amplification can be reduced by raising the annealing temperature. In cases where one is amplifying libraries with the same tag as the target specific primers, the annealing temperature can be increased in comparison to the genomic DNA as the tags will contribute to the primer binding. In some embodiments we are using considerably lower primer concentrations than previously reported along with using longer annealing times than reported elsewhere. In some embodiments the annealing times may be longer than 3 minutes, longer than 5 minutes, longer than 8 minutes, longer than 10 minutes, longer than 15 minutes, longer than 20 minutes, longer than 30 minutes, longer than 60 minutes, longer than 120 minutes, longer than 240 minutes, longer than 480 minutes, and even longer than 960 minutes. In an embodiment, longer annealing times are used than in previous reports, allowing lower primer concentrations. In various embodiments, longer than normal extension times are used, such as greater than 3, 5, 8, 10, or 15 minutes. In some embodiments, the primer concentrations are as low as 50 nM, 20 nM, 10 nM, 5 nM, 1 nM, and lower than 1 uM. This surprisingly results in robust performance for highly multiplexed reactions, for example 1,000-plex reactions, 2,000-plex reactions, 5,000-plex reactions, 10,000-plex reactions, 20,000-plex reactions, 50,000-plex reactions, and even 100,000-plex reactions. In an embodiment, the amplification uses one, two, three, four or five cycles run with long annealing times, followed by PCR cycles with more usual annealing times with tagged primers.

[00305] To select target locations, one may start with a pool of candidate primer pair designs and create a thermodynamic model of potentially adverse interactions between primer pairs, and then use the model to eliminate designs that are incompatible with other the designs in the pool.

Exemplary Primer Libraries

[00306] In one aspect, the invention features libraries of primers, such as primers selected from a library of candidate primers using any of the methods of the invention. In some embodiments, the library includes primers that simultaneously hybridize (or are capable of simultaneously

hybridizing) to or that simultaneously amplify (or are capable of simultaneously amplifying) at least 100; 200; 500; 750; 1,000; 2,000; 5,000; 7,500; 10,000; 20,000; 25,000; 30,000; 40,000; 50,000; 75,000; or 100,000 different target loci in one reaction volume. In various embodiments, the library includes primers that simultaneously amplify (or are capable of simultaneously amplifying) between 100 to 500; 500 to 1,000; 1,000 to 2,000; 2,000 to 5,000; 5,000 to 7,500; 7,500 to 10,000; 10,000 to 20,000; 20,000 to 25,000; 25,000 to 30,000; 30,000 to 40,000; 40,000 to 50,000; 50,000 to 75,000; or 75,000 to 100,000 different target loci in one reaction volume, inclusive. In various embodiments, the library includes primers that simultaneously amplify (or are capable of simultaneously amplifying) between 1,000 to 100,000 different target loci in one reaction volume, such as between 1,000 to 50,000; 1,000 to 30,000; 1,000 to 20,000; 1,000 to 10,000; 2,000 to 30,000; 2,000 to 20,000; 2,000 to 10,000; 5,000 to 30,000; 5,000 to 20,000; or 5,000 to 10,000 different target loci, inclusive. In some embodiments, the library includes primers that simultaneously amplify (or are capable of simultaneously amplifying) the target loci in one reaction volume such that less than 60, 40, 30, 20, 10, 5, 4, 3, 2, 1, 0.5, 0.25, 0.1, or 0.5% of the amplified products are primer dimers. The various embodiments, the amount of amplified products that are primer dimers is between 0.5 to 60%, such as between 0.1 to 40%, 0.1 to 20%, 0.25 to 20%, 0.25 to 10%, 0.5 to 20%, 0.5 to 10%, 1 to 20%, or 1 to 10%, inclusive. In some embodiments, the primers simultaneously amplify (or are capable of simultaneously amplifying) the target loci in one reaction volume such that at least 50, 60, 70, 80, 90, 95, 96, 97, 98, 99, or 99.5% of the amplified products are target amplicons. In various embodiments, the amount of amplified products that are target amplicons is between 50 to 99.5%, such as between 60 to 99%, 70 to 98%, 80 to 98%, 90 to 99.5%, or 95 to 99.5%, inclusive. In some embodiments, the primers simultaneously amplify (or are capable of simultaneously amplifying) the target loci in one reaction volume such that at least 50, 60, 70, 80, 90, 95, 96, 97, 98, 99, or 99.5% of the targeted loci are amplified (*e.g.*, amplified at least 5, 10, 20, 30, 50, or 100-fold compared to the amount prior to amplification). In various embodiments, the amount target loci that are amplified (*e.g.*, amplified at least 5, 10, 20, 30, 50, or 100-fold compared to the amount prior to amplification) is between 50 to 99.5%, such as between 60 to 99%, 70 to 98%, 80 to 99%, 90 to 99.5%, 95 to 99.9%, or 98 to 99.99% inclusive. In some embodiments, the library of primers includes at least 100; 200; 500; 750; 1,000; 2,000; 5,000; 7,500; 10,000; 20,000; 25,000; 30,000; 40,000; 50,000; 75,000; or 100,000 primer pairs, wherein each pair of primers includes a forward

test primer and a reverse test primer where each pair of test primers hybridize to a target locus. In some embodiments, the library of primers includes at least 100; 200; 500; 750; 1,000; 2,000; 5,000; 7,500; 10,000; 20,000; 25,000; 30,000; 40,000; 50,000; 75,000; or 100,000 individual primers that each hybridize to a different target locus, wherein the individual primers are not part of primer pairs.

[00307] In various embodiments, the concentration of each primer is less than 100, 75, 50, 25, 20, 10, 5, 2, or 1 nM, or less than 500, 100, 10, or 1 uM. In various embodiments, the concentration of each primer is between 1 uM to 100 nM, such as between 1 uM to 1 nM, 1 to 75 nM, 2 to 50 nM or 5 to 50 nM, inclusive. In various embodiments, the GC content of the primers is between 30 to 80%, such as between 40 to 70%, or 50 to 60%, inclusive. In some embodiments, the range of GC content of the primers is less than 30, 20, 10, or 5%. In some embodiments, the range of GC content of the primers is between 5 to 30%, such as 5 to 20% or 5 to 10%, inclusive. In some embodiments, the melting temperature (T_m) of the test primers is between 40 to 80 °C, such as 50 to 70 °C, 55 to 65 °C, or 57 to 60.5 °C, inclusive. In some embodiments, the T_m is calculated using the Primer3 program (libprimer3 release 2.2.3) using the built-in SantaLucia parameters (the world wide web at primer3.sourceforge.net). In some embodiments, the range of melting temperature of the primers is less than 15, 10, 5, 3, or 1 °C. In some embodiments, the range of melting temperature of the primers is between 1 to 15 °C, such as between 1 to 10 °C, 1 to 5 °C, or 1 to 3 °C, inclusive. In some embodiments, the length of the primers is between 15 to 100 nucleotides, such as between 15 to 75 nucleotides, 15 to 40 nucleotides, 17 to 35 nucleotides, 18 to 30 nucleotides, or 20 to 65 nucleotides, inclusive. In some embodiments, the range of the length of the primers is less than 50, 40, 30, 20, 10, or 5 nucleotides. In some embodiments, the range of the length of the primers is between 5 to 50 nucleotides, such as 5 to 40 nucleotides, 5 to 20 nucleotides, or 5 to 10 nucleotides, inclusive. In some embodiments, the length of the target amplicons is between 50 and 100 nucleotides, such as between 60 and 80 nucleotides, or 60 to 75 nucleotides, inclusive. In some embodiments, the range of the length of the target amplicons is less than 50, 25, 15, 10, or 5 nucleotides. In some embodiments, the range of the length of the target amplicons is between 5 to 50 nucleotides, such as 5 to 25 nucleotides, 5 to 15 nucleotides, or 5 to 10 nucleotides, inclusive. In some embodiments, the library does not comprise a microarray.

[00308] Additional exemplary multiplex PCR methods and libraries are described in US Application No. 13/683,604, filed Nov. 21, 2012 (U.S. Publication No. 2013/0123120, which is hereby incorporated by reference in its entirety). These methods and libraries can be used for analysis of any of the samples disclosed herein and for use in any of the methods of the invention.

Exemplary Primer Kits

[00309] In one aspect, the invention features a kit (such as kits for amplifying target loci in a nucleic acid sample for detecting deletions and/or duplications of chromosome segments or entire chromosomes using any of the methods described herein). In some embodiments, the kits include any of the primer libraries of the invention. In an embodiment, the kit comprises a plurality of inner forward primers and optionally a plurality of inner reverse primers, and optionally outer forward primers and outer reverse primers, where each of the primers is designed to hybridize to the region of DNA immediately upstream and/or downstream from one of the target sites (e.g., polymorphic sites) on the target chromosome(s) or chromosome segment(s), and optionally additional chromosomes or chromosome segments. In some embodiments, the kit includes instructions for using the primer library to amplify the target loci, such as for detecting one or more deletions and/or duplications of one or more chromosome segments or entire chromosomes using any of the methods described herein.

Exemplary Normalization/Correction Methods

[00310] In some embodiments, measurements for different loci, chromosome segments, or chromosomes are adjusted for bias, such as bias due to differences in GC content or bias due to other differences in amplification efficiency or adjusted for sequencing errors. In some embodiments, measurements for different alleles for the same locus are adjusted for differences in metabolism, apoptosis, histones, inactivation, and/or amplification between the alleles. In some embodiments, measurements for different alleles for the same locus in RNA are adjusted for differences in transcription rates or stability between different RNA alleles.

Exemplary Methods for Phasing Genetic Data

[00311] In some embodiments, genetic data is phased using the methods described herein or any known method for phasing genetic data (*see, e.g.*, PCT Publ. No. WO2009/105531, filed February 9, 2009, and PCT Publ. No. WO2010/017214, filed August 4, 2009; U.S. Publ. No. 2013/0123120, Nov. 21, 2012; U.S. Publ. No. 2011/ 0033862, filed Oct. 7, 2010; U.S. Publ. No. 2011/0033862, filed August 19, 2010; U.S. Publ. No. 2011/0178719, filed Feb. 3, 2011; U.S. Pat. No. 8,515,679, filed March 17, 2008; U.S. Publ. No. 2007/0184467, filed Nov. 22, 2006; U.S. Publ. No. 2008/0243398, filed March 17, 2008, which are each hereby incorporated by reference in its entirety). In one embodiment, genetic data of an individual (*e.g.*, an individual being tested using the methods of the invention or a relative of a gestating fetus or embryo, such as a parent of the fetus or embryo) is phased by inference by measuring tissue from the individual that is haploid, for example by measuring one or more sperm or eggs. In one embodiment, an individual's genetic data is phased by inference using the measured genotypic data of one or more first degree relatives, such as the individual's parents (*e.g.*, sperm from the individual's father) or siblings.

[00312] In one embodiment, an individual's genetic data is phased by dilution where the DNA is diluted in one or a plurality of wells, such as by using digital PCR. In some embodiments, the DNA is diluted to the point where there is expected to be no more than approximately one copy of each haplotype in each well, and then the DNA in the one or more wells is measured. In some embodiments, cells are arrested at phase of mitosis when chromosomes are tight bundles, and microfluidics is used to put separate chromosomes in separate wells. Because the DNA is diluted, it is unlikely that more than one haplotype is in the same fraction (or tube). Thus, there may be effectively a single molecule of DNA in the tube, which allows the haplotype on a single DNA molecule to be determined. In some embodiments, the method includes dividing a DNA sample into a plurality of fractions such that at least one of the fractions includes one chromosome or one chromosome segment from a pair of chromosomes, and genotyping (*e.g.*, determining the presence of two or more polymorphic loci) the DNA sample in at least one of the fractions, thereby determining a haplotype. In some embodiments, the genotyping involves sequencing (such as shotgun sequencing), a SNP array to detect polymorphic loci, or multiplex PCR. In some embodiments, the genotyping involves use of a SNP array to detect polymorphic loci, such as at least 100; 200; 500; 750; 1,000; 2,000; 5,000; 7,500; 10,000; 20,000; 25,000; 30,000; 40,000; 50,000; 75,000; or 100,000 different polymorphic loci. In some embodiments,

the genotyping involves the use of multiplex PCR. In some embodiments, the method involves contacting the sample in a fraction with a library of primers that simultaneously hybridize to at least 100; 200; 500; 750; 1,000; 2,000; 5,000; 7,500; 10,000; 20,000; 25,000; 30,000; 40,000; 50,000; 75,000; or 100,000 different polymorphic loci (such as SNPs) to produce a reaction mixture; and subjecting the reaction mixture to primer extension reaction conditions to produce amplified products that are measured with a high throughput sequencer to produce sequencing data.

[00313] In some embodiments, a haplotype of the individual is determined using data from a relative of the individual. In some embodiments, a SNP array is used to determine the presence of at least 100; 200; 500; 750; 1,000; 2,000; 5,000; 7,500; 10,000; 20,000; 25,000; 30,000; 40,000; 50,000; 75,000; or 100,000 different polymorphic loci in a DNA sample from the individual and a relative of the individual. In some embodiments, the method involves contacting a DNA sample from the individual and/or a relative of the individual with a library of primers that simultaneously hybridize to at least 100; 200; 500; 750; 1,000; 2,000; 5,000; 7,500; 10,000; 20,000; 25,000; 30,000; 40,000; 50,000; 75,000; or 100,000 different polymorphic loci (such as SNPs) to produce a reaction mixture; and subjecting the reaction mixture to primer extension reaction conditions to produce amplified products that are measured with a high throughput sequencer to produce sequencing data.

[00314] In one embodiment, an individual's genetic data is phased using a computer program that uses population based haplotype frequencies to infer the most likely phase, such as HapMap-based phasing. For example, haploid data sets can be deduced directly from diploid data using statistical methods that utilize known haplotype blocks in the general population (such as those created for the public HapMap Project and for the Perlegen Human Haplotype Project). A haplotype block is essentially a series of correlated alleles that occur repeatedly in a variety of populations. Since these haplotype blocks are often ancient and common, they may be used to predict haplotypes from diploid genotypes. Publicly available algorithms that accomplish this task include an imperfect phylogeny approach, Bayesian approaches based on conjugate priors, and priors from population genetics. Some of these algorithms use a hidden Markov model.

[00315] In various embodiments, an individual's genetic data is phased using data about the probability of chromosomes crossing over at different locations in a chromosome or chromosome segment (such as using recombination data such as may be found in the HapMap

database to create a recombination risk score for any interval) to model dependence between polymorphic alleles on the chromosome or chromosome segment. In some embodiments, allele counts at the polymorphic loci are calculated on a computer based on sequencing data or SNP array data. In some embodiments, a plurality of hypotheses each pertaining to a different possible state of the chromosome or chromosome segment (such as an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in the genome of one or more cells from an individual, a duplication of the first homologous chromosome segment, a deletion of the second homologous chromosome segment, or an equal representation of the first and second homologous chromosome segments) are created (such as creation on a computer); a model (such as a joint distribution model) for the expected allele counts at the polymorphic loci on the chromosome is built (such as building on a computer) for each hypothesis; a relative probability of each of the hypotheses is determined (such as determination on a computer) using the joint distribution model and the allele counts; and the hypothesis with the greatest probability is selected. In some embodiments, building a joint distribution model for allele counts and the step of determining the relative probability of each hypothesis are done using a method that does not require the use of a reference chromosome.

[00316] In one embodiment, genetic data of an individual is phased using genetic data of one or more genetic offspring of the individual (*e.g.*, 1, 2, 3, or more offspring), such as embryos, fetuses, born children, or a sample of a miscarriage. In one embodiment, genetic data of a parent (such as a parent of a gestating fetus or embryo) is phased using phased haplotypic data for the other parent along with unphased genetic data of one or more genetic offspring of the parents.

[00317] In another embodiment for prenatal diagnostics, phased parental haplotypic data is to detect the presence of more than one homolog from the father, implying that the genetic material from more than one fetus is present in a maternal blood sample. By focusing on chromosomes that are expected to be euploid in a fetus, one could rule out the possibility that the fetus was afflicted with a trisomy. Also, it is possible to determine if the fetal DNA is not from the current father.

Exemplary Methods for Phasing, Predicting Allele Ratios, and Reconstructing Fetal Genetic Data

[00318] In one aspect, the invention features methods for determining one or more haplotypes of a fetus. In various embodiments, this method allows one to determine which polymorphic loci (such as SNPs) were inherited by the fetus and to reconstruct which homologs (including recombination events) are present in the fetus (and thereby interpolate the sequence between the polymorphic loci). If desired, essentially the entire genome of the fetus can be reconstructed. If there is some remaining ambiguity in the genome of the fetus (such as in intervals with a crossover), this ambiguity can be minimized if desired by analyzing additional polymorphic loci. In various embodiments, the polymorphic loci are chosen to cover one or more of the chromosomes at a density to reduce any ambiguity to a desired level. This method has important applications for the detection of polymorphisms or other mutations of interest (such as deletions or duplications) in a fetus since it enables their detection based on linkage (such as the presence of linked polymorphic loci in the fetal genome) rather than by directly detecting the polymorphism or other mutation of interest in the fetal genome. For example, if a parent is a carrier for a mutation associated with cystic fibrosis (CF), a nucleic acid sample that includes maternal DNA from the mother of the fetus and fetal DNA from the fetus can be analyzed to determine whether the fetal DNA includes the haplotype containing the CF mutation. In particular, polymorphic loci can be analyzed to determine whether the fetal DNA includes the haplotype containing the CF mutation without having to detect the CF mutation itself in the fetal DNA.

[00319] In some embodiments, the method involves determining a parental haplotype (*e.g.*, a haplotype of the mother or father of the fetus), such as by using any of the methods described herein. In some embodiments, this determination is made without using data from a relative of the mother or father. In some embodiments, a parental haplotype is determined using a dilution approach followed by SNP genotyping or sequencing as described herein. In some embodiments, a haplotype of the mother (or father) is determined by any of the methods described herein using data from a relative of the mother (or father). In some embodiments, a haplotype is determined for both the father and the mother.

[00320] This parental haplotype data can be used to determine if the fetus inherited the parental haplotype. In some embodiments, a nucleic acid sample that includes maternal DNA from the mother of the fetus and fetal DNA from the fetus is analyzed using a SNP array to detect at least 100; 200; 500; 750; 1,000; 2,000; 5,000; 7,500; 10,000; 20,000; 25,000; 30,000;

40,000; 50,000; 75,000; or 100,000 different polymorphic loci. In some embodiments, a nucleic acid sample that includes maternal DNA from the mother of the fetus and fetal DNA from the fetus is analyzed by contacting the sample with a library of primers that simultaneously hybridize to at least 100; 200; 500; 750; 1,000; 2,000; 5,000; 7,500; 10,000; 20,000; 25,000; 30,000; 40,000; 50,000; 75,000; or 100,000 different polymorphic loci (such as SNPs) to produce a reaction mixture. In some embodiments, the reaction mixture is subjected to primer extension reaction conditions to produce amplified products. In some embodiments, the amplified products are measured with a high throughput sequencer to produce sequencing data.

[00321] In various embodiments, a fetal haplotype is determined using data about the probability of chromosomes crossing over at different locations in a chromosome or chromosome segment (such as by using recombination data such as may be found in the HapMap database to create a recombination risk score for any interval) to model dependence between polymorphic alleles on the chromosome or chromosome segment as described above. In some embodiments, the method takes into account physical distance of the SNPs (such as SNPs flanking a gene or mutation of interest) and recombination data from location specific recombination likelihoods and the data observed from the genetic measurements of the maternal plasma to obtain the most likely genotype of the fetus. Then PARENTAL SUPPORT™ may be performed on the targeted sequencing or SPN array data obtained from these SNPs to determine which homologs were inherited by the fetus from both parents (*see, e.g.*, U.S. Application No. 11/603,406 (US Publication No. 20070184467), U.S. Application No. 12/076,348 (US Publication No. 20080243398), U.S. Application 13/110,685 (U.S. Publication No. 2011/0288780), PCT Application PCT/US09/52730 (PCT Publication No. WO/2010/017214), and PCT Application No. PCT/US10/050824 (PCT Publication No. WO/2011/041485), U.S. Application No. 13/300,235 (U.S. Publication No. 2012/0270212), U.S. Application No. 13/335,043 (U.S. Publication No. 2012/0122701), U.S. Application No. 13/683,604, and U.S. Application No. 13/780,022, which are each hereby incorporated by reference in its entirety).

[00322] Assume a generalized example where the possible alleles at one locus are A and B; assignment of the identity A or B to particular alleles is arbitrary. Parental genotypes for a particular SNP, termed genetic contexts, are expressed as maternal genotype|paternal genotype. Thus, if the mother is homozygous and the father is heterozygous, this would be represented as AA|AB. Similarly, if both parents are homozygous for the same allele, the parental genotypes

would be represented as AA|AA. Furthermore, the fetus would never have AB or BB states and the number of sequence reads with the B allele will be low, and thus can be used to determine the noise responses of the assay and genotyping platform, including effects such as low level DNA contamination and sequencing errors; these noise responses are useful for modeling expected genetic data profiles. There are only five possible maternal|paternal genetic contexts: AA|AA, AA|AB, AB|AA, AB|AB, and AA|BB; other contexts are equivalent by symmetry. SNPs where the parents are homozygous for the same allele are only informative for determining noise and contamination levels. SNPs where the parents are not homozygous for the same allele are informative in determining fetal fraction and copy number count.

[00323] Let $N_{A,i}$ and $N_{B,i}$ represent the number of reads of each allele at SNP i , and let C_i represent the parental genetic context at that locus. The data set for a particular chromosome is represented by $N_{AB} = \{N_{A,i}, N_{B,i}\} i=1 \dots N$ and $C = \{C_i\}, i=1 \dots N$. For reconstructing part or all of the fetal genome, it can optionally be determined if the fetus has an aneuploidy (such as a missing or extra copy of a chromosome or chromosome segment). For each individual chromosome or chromosome under study, let H represent the set of one or more hypotheses for the total number of chromosomes, the parental origin of each chromosome, and the positions on the parent chromosomes where recombination occurred during formation of the gametes that fertilized to create the child. The probability of a hypothesis $P(H)$ can be computed using the data from the HapMap database and prior information related to each of the ploidy states.

[00324] Furthermore, let F represent the fetal cfDNA fraction in the sample. Given a set of possible H , C , and F , one can compute the probability of N_{AB} , $P(N_{AB}|H,F,C)$ based on modeling the noise sources of the molecular assay and the sequencing platform. The goal is to find the hypothesis H and the fetal fraction F that maximizes $P(H,F|N_{AB})$. Using standard Bayesian statistical techniques, and assuming a uniform probability distribution for F from 0 to 1, this can be recast in terms of maximizing the probability of $P(N_{AB}|H,F,C)P(H)$ over H and F , all of which can now be computed. The probability of all hypotheses associated with a particular copy number and fetal fraction, *e.g.*, trisomy and $F=10\%$, but covering all possible parental chromosome origins and crossover locations, are summed. The copy number hypothesis with the highest probability is selected as the test result, the fetal fraction associated with that hypothesis reveals the fetal fraction, and the probability associated with that hypothesis is the calculated accuracy of the result.

[00325] In some embodiments, the algorithm uses *in silico* simulations to generate a very large number of hypothetical sequencing data sets that could result from the possible fetal genetic inheritance patterns, sample parameters, and amplification and measurement artifacts of the method. More specifically, the algorithm first utilizes parental genotypes at a large number of SNPs and crossover frequency data from the HapMap database to predict possible fetal genotypes. It then predicts expected data profiles for the sequencing data that would be measured from mixed samples originating from a mother carrying a fetus with each of the possible fetal genotypes and taking into account a variety of parameters including fetal fraction, expected read depth profile, fetal genome equivalents present in the sample, expected amplification bias at each of the SNPs, and a number of noise parameters. A data model describes how the sequencing or SNP array data is expected to appear for each of these hypotheses given the particular parameter set. The hypothesis with the best data fit between this modeled data and the measured data is selected.

[00326] If desired, expected allele ratios can be calculated for DNA or RNA from the fetus using the results of what haplotypes were inherited by the fetus. The expected allele ratios can also be calculated for a mixed sample containing nucleic acids from both the mother and the fetus (these allele ratios indicate what is expected for measurement of the total amount of each allele, including the amount of the allele from both maternal nucleic acids and fetal nucleic acids in the sample). The expected allele ratios can be calculated for different hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment.

[00327] In some embodiments, the method involves determining whether the fetus has one or more of the following conditions: cystic fibrosis, Huntington's disease, Fragile X, thalassemia, muscular dystrophy, Alzheimer, Fanconi Anemia, Gaucher Disease, Mucopolysaccharidosis IV, Niemann-Pick Disease, Tay-Sachs disease, Sickle cell anemia, Parkinson disease, Torsion Dystonia, and cancer. In some embodiments, a fetal haplotype is determined for one or more chromosomes taken from the group consisting of chromosomes 13, 18, 21, X, and Y. In some embodiments, a fetal haplotype is determined for all of the fetal chromosomes. In various embodiments, the method determines essentially the entire genome of the fetus. In some embodiments, the haplotype is determined for at least 30, 40, 50, 60, 70, 80, 90, or 95% of the genome of the fetus. In some embodiments, the haplotype determination of the fetus includes information about which allele is present for at least 100; 200; 500; 750; 1,000; 2,000; 5,000;

7,500; 10,000; 20,000; 25,000; 30,000; 40,000; 50,000; 75,000; or 100,000 different polymorphic loci. In some embodiments, this method is used to determine a haplotype or allele ratios for an embryo.

Exemplary Methods for Predicting Allele Ratios

[00328] Exemplary methods are described below for calculating expected allele ratios for a sample. Table 1 shows expected allele ratios for a mixed sample (such as a maternal blood sample) containing nucleic acids from both the mother and the fetus. These expected allele ratios indicate what is expected for measurement of the total amount of each allele, including the amount of the allele from both maternal nucleic acids and fetal nucleic acids in the mixed sample. In an example, the mother is heterozygous at two neighboring loci that are expected to cosegregate (*e.g.*, two loci for which no chromosome crossovers are expected between the loci). Thus, the mother is (AB,AB). Now imagine that the phased data for the mother indicates that for one haplotype she is (A,A); thus, for the other haplotype one can infer that she is (B,B). Table 1 gives the expected allele ratios for different hypotheses where the fetal fraction is 20%. For this example, no knowledge of the paternal data is assumed, and the heterozygosity rate is assumed to be 50%. The expected allele ratios are given in terms of (expected proportion of A reads / total number of reads) for each of the two SNPs. These ratios are calculated both using maternal phased data (the knowledge that one haplotype is (A,A) and one is (B,B)) and without using the maternal phased data. Table 1 includes different hypotheses for the number of copies of the chromosome segment in the fetus from each parent.

Table 1: Expected Genetic Data for Mixed Sample of Maternal and Fetal Nucleic Acids

Copy Number Hypothesis	Expected allele ratios when using maternal phased data	Expected allele ratios when not using maternal phased data
Monosomy (maternal copy missing)	(0.444; 0.444) (0.444; 0.555) (0.555; 0.444) (0.555; 0.555)	(0.444; 0.444) (0.444; 0.555) (0.555; 0.444) (0.555; 0.555)
Monosomy (paternal copy missing)	(0.444; 0.444) (0.555; 0.555)	(0.444; 0.444) (0.444; 0.555)

		(0.555; 0.444) (0.555; 0.555)
Disomy	(0.40; 0.40) (0.40; 0.50) (0.50; 0.40) (0.50; 0.50) (0.50; 0.60) (0.60; 0.50) (0.60; 0.60)	(0.40; 0.40) (0.40; 0.50) (0.40; 0.60) (0.50; 0.40) (0.50; 0.50) (0.50; 0.60) (0.60; 0.40) (0.60; 0.50) (0.60; 0.60)
Trisomy (extra matching maternal copy)	(0.36; 0.36) (0.36; 0.45) (0.45; 0.36) (0.45; 0.45) (0.54; 0.54) (0.54; 0.63) (0.63; 0.54) (0.63; 0.63)	(0.36; 0.36) (0.36; 0.45) (0.36; 0.54) (0.36; 0.63) (0.45; 0.36) (0.45; 0.45) (0.45; 0.54) (0.45; 0.63) (0.54; 0.36) (0.54; 0.45) (0.54; 0.54) (0.54; 0.63) (0.63; 0.36) (0.63; 0.45) (0.63; 0.54) (0.63; 0.63)
Trisomy (extra unmatching maternal copy)	(0.45; 0.45) (0.45; 0.54) (0.54; 0.45) (0.54; 0.54)	(0.36; 0.36) (0.36; 0.45) (0.36; 0.54) (0.36; 0.63)

		(0.45; 0.36) (0.45; 0.45) (0.45; 0.54) (0.45; 0.63) (0.54; 0.36) (0.54; 0.45) (0.54; 0.54) (0.54; 0.63) (0.63; 0.36) (0.63; 0.45) (0.63; 0.54) (0.63; 0.63)
Trisomy (extra matching paternal copy)	(0.36; 0.36) (0.36; 0.54) (0.54; 0.36) (0.54; 0.54) (0.45; 0.45) (0.45; 0.63) (0.63; 0.45) (0.63; 0.63)	(0.36; 0.36) (0.36; 0.45) (0.36; 0.54) (0.36; 0.63) (0.45; 0.36) (0.45; 0.45) (0.45; 0.54) (0.45; 0.63) (0.54; 0.36) (0.54; 0.45) (0.54; 0.54) (0.54; 0.63) (0.63; 0.36) (0.63; 0.45) (0.63; 0.54) (0.63; 0.63)
Trisomy (extra unmatching paternal copy)	(0.36; 0.36) (0.36; 0.45) (0.36; 0.54)	(0.36; 0.36) (0.36; 0.45) (0.36; 0.54)

	(0.36; 0.63)	(0.36; 0.63)
	(0.45; 0.36)	(0.45; 0.36)
	(0.45; 0.45)	(0.45; 0.45)
	(0.45; 0.54)	(0.45; 0.54)
	(0.45; 0.63)	(0.45; 0.63)
	(0.54; 0.36)	(0.54; 0.36)
	(0.54; 0.45)	(0.54; 0.45)
	(0.54; 0.54)	(0.54; 0.54)
	(0.54; 0.63)	(0.54; 0.63)
	(0.63; 0.36)	(0.63; 0.36)
	(0.63; 0.45)	(0.63; 0.45)
	(0.63; 0.54)	(0.63; 0.54)
	(0.63; 0.63)	(0.63; 0.63)

[00329] In addition to the fact that using phased data reduces the number of possible expected allele ratios, it also changes the prior likelihood of each of the expected allele ratios, such that the maximum likelihood result is more likely to be correct. Eliminating expected allele ratios or hypotheses that are not possible increases the likelihood that the correct hypothesis will be chosen. As an example, suppose the measured allele ratios are (0.41, 0.59). Without using phased data, one might assume that the hypothesis with maximum likelihood is a disomy hypothesis (given the similarity of the measured allele ratios to expected allele ratios of (0.40, 0.60) for disomy). However, using phased data, one can exclude (0.40, 0.60) as expected allele ratios for the disomy hypothesis, and one can select a trisomy hypothesis as more likely.

[00330] Assume the measured allele ratios are (0.4, 0.4). Without any haplotype information, the probability of a maternal deletion at each SNP would be the $0.5 \times P(A \text{ deleted}) + 0.5 \times P(B \text{ deleted})$. So basically, although it looks like A is deleted (missing in the fetus), the likelihood of deletion would be the average of the two. For high enough fetal fraction, one can still determine the most likely hypothesis. For low enough fetal fraction, averaging may work in disfavor of the deletion hypothesis. However, with haplotype information, the probability of homolog 1 being deleted, $P(A \text{ deleted})$, is greater and will fit the measured data better. If desired, crossover probabilities between the two loci can also be considered.

[00331] The following exemplary methods are described below can also be used to calculate expected allele ratios for a sample and to determine the probability of hypotheses.

Hypotheses

[00332] For notation, one can use $G_{(c_{m1}, c_{m2})(c_{f1}, c_{f2})}$ where c_{mi} and c_{fi} denotes the copy number from mother's and father's homolog $i \in \{1, 2\}$. For example, $G_{(0,1),(0,1)}$ refers to the case where child has homolog 2 from both parents. Note that these refer to SNP level hypotheses (such as matched and unmatched trisomy hypotheses), and one combines these to find the actual deletion probability on a chromosome. Note that H_{10} hypothesis includes $G_{(1,0),(0,0)}$ and $G_{(0,1),(0,0)}$, H_{01} hypothesis includes $G_{(0,0),(1,0)}$ and $G_{(0,0),(0,1)}$, H_{11} hypothesis includes $G_{(1,0),(1,0)}$, $G_{(1,0),(0,1)}$, $G_{(0,1),(1,0)}$ and $G_{(0,1),(0,1)}$.

Combining SNP Level Hypotheses

[00333] Let's consider H_{10} to begin with. Assume there are N SNPs and let C denote the centromere location. Let G_i denote the hypotheses at SNP i . Let p_i denote the crossover probability at SNP i . In this case, the possible hypotheses are $G_{(1,0),(0,0)}$ and $G_{(0,1),(0,0)}$. Let $E_1, E_2 \in \{(1,0), (0,1)\}$ denote the haplotype inherited from a parent. One can find

$$P(D_{1,...,N}|H_{10}) = \sum_{E_1, E_2} P(D_{1,...,C}|G_C = G_{E_1,(0,0)})P(G_{E_1,(0,0)} \Rightarrow G_{E_2,(0,0)}, C, C+1)P(D_{C+1,...,N}|G_{C+1} = G_{E_2,(0,0)}).$$

[00334] We have $P(G_{E_1,(0,0)} \Rightarrow G_{E_2,(0,0)}, C, C+1) = 1 - p_C$ if $E_1 = E_2$, and $P(G_{E_1,(0,0)} \Rightarrow G_{E_2,(0,0)}, C, C+1) = p_C$ if $E_1 \neq E_2$. Note that $P(D_1|G_1 = G_{E,(0,0)})$ for $E \in \{(1,0), (0,1)\}$ can be calculated simply. Let E^C denote the complement of E . Then, we have

$$P(D_{1,2}|G_2 = G_{E,(0,0)}) = P(D_2|G_2 = G_{E,(0,0)}) \left(P(D_1|G_1 = G_{E,(0,0)})(1 - p_1) + P(D_1|G_1 = G_{E^C,(0,0)})p_1 \right),$$

and recursively we can determine $P(D_{1,...,C}|G_C)$ as follows:

$$P(D_{1,...,C}|G_C = G_{E,(0,0)}) = P(D_C|G_C = G_{E,(0,0)}) \times \left(P(D_{1,...,C-1}|G_{C-1} = G_{E,(0,0)})(1 - p_{C-1}) + P(D_{1,...,C-1}|G_{C-1} = G_{E^C,(0,0)})p_{C-1} \right).$$

[00335] Similarly, we can determine $P(D_N|G_N)$ can be calculated simply and we can determine $P(D_{C+1,\dots,N}|G_{C+1})$ using recursion. Similar calculations can be used for H_{01} , the only difference is that the possible hypotheses are $G_{(0,0),(1,0)}$ and $G_{(0,0),(0,1)}$.

[00336] For H_{11} , possible hypotheses are $G_{(1,0),(1,0)}$, $G_{(1,0),(0,1)}$, $G_{(0,1),(1,0)}$ and $G_{(0,1),(0,1)}$. $E_1, E_2, E_3, E_4 \in \{(1,0), (0,1)\}$. We can find

$$P(D_{1,\dots,N}|H_{11}) = \sum_{E_1, E_2, E_3, E_4} P(D_{1,\dots,C}|G_C = G_{E_1, E_2}) P(G_{E_1, E_2} \Rightarrow G_{E_3, E_4}, C, C+1) P(D_{C+1,\dots,N}|G_{C+1} = G_{E_3, E_4}).$$

Note that $P(G_{E_1, E_2} \Rightarrow G_{E_3, E_4}, C, C+1) = (1 - p_C)^2$ for $E_1 = E_3$ and $E_2 = E_4$; $P(G_{E_1, E_2} \Rightarrow G_{E_3, E_4}, C, C+1) = (1 - p_C)p_C$ for $E_1 = E_3$ and $E_2 \neq E_4$ or $E_1 \neq E_3$ and $E_2 = E_4$; and $P(G_{E_1, E_2} \Rightarrow G_{E_3, E_4}, C, C+1) = p_C^2$ for $E_1 \neq E_3$ and $E_2 \neq E_4$.

Exemplary Polymorphisms or Mutations

[00337] Exemplary polymorphisms or mutations associated with a disease or disorder such as cancer or an increased risk for a disease or disorder such as cancer include single nucleotide polymorphisms (SNPs), multiple nucleotide mutations, deletions (such as deletion of a 2 to 30 million base pair region), duplications, or tandem repeats. In some embodiments, the polymorphism or mutation is in DNA, such as cfDNA, cell-free mitochondrial DNA (cf mDNA), cell-free DNA that originated from nuclear DNA (cf nDNA), cellular DNA, or mitochondrial DNA. In some embodiments, the polymorphism or mutation is in RNA, such as cfRNA, cellular RNA, cytoplasmic RNA, coding cytoplasmic RNA, non-coding cytoplasmic RNA, mRNA, miRNA, mitochondrial RNA, rRNA, or tRNA. In some embodiments, the polymorphism or mutation is a driver mutation that has a causative role in the disease or disorder. In some embodiments, the polymorphism or mutation is not a causative mutation. For example, in some cancers, multiple mutations accumulate but some of them are not causative mutations. Polymorphisms or mutations (such as those that are present at a higher frequency in subjects with a disease or disorder than subjects with the disease or disorder) that are not causative can still be useful for diagnosing the disease or disorder. In some embodiments, the mutation is loss-of-heterozygosity (LOH) at one or more microsatellites.

[00338] In some embodiments, a subject is screened for one of more polymorphisms or mutations that the subject is known to have (*e.g.*, to test for their presence, a change in the amount of cells, DNA, or RNA with these polymorphisms or mutations, or cancer remission or re-occurrence). In some embodiments, a subject is screened for one of more polymorphisms or mutations that the subject is known to be at risk for (such as a subject who has a relative with the polymorphism or mutation). In some embodiments, a subject is screened for a panel of polymorphisms or mutations associated with a disease or disorder such as cancer (*e.g.*, at least 5, 10, 50, 100, 200, 300, 500, 750, 1,000, 1,500, 2,000, or 5,000 polymorphisms or mutations).

[00339] Many coding variants associated with cancer are described in Abaan *et al.*, "The Exomes of the NCI-60 Panel: A Genomic Resource for Cancer Biology and Systems Pharmacology", *Cancer Research*, July 15, 2013, and world wide web at dtp.nci.nih.gov/branches/btb/characterizationNCI60.html, which are each hereby incorporated by reference in its entirety). The NCI-60 human cancer cell line panel consists of 60 different cell lines representing cancers of the lung, colon, brain, ovary, breast, prostate, and kidney, as well as

leukemia and melanoma. The genetic variations that were identified in these cell lines consisted of two types: type I variants that are found in the normal population, and type II variants that are cancer-specific.

[00340] Exemplary polymorphisms or mutations are in one or more of the following genes: TP53, PTEN, PIK3CA, APC, EGFR, NRAS, NF2, FBXW7, ERBBs, ATAD5, KRAS, BRAF, VEGF, EGFR, HER2, ALK, p53, BRCA, BRCA1, BRCA2, SETD2, LRP1B, PBRM, SPTA1, DNMT3A, ARID1A, GRIN2A, TRRAP, STAG2, EPHA3/5/7, POLE, SYNE1, C20orf80, CSMD1, CTNNB1, ERBB2, FBXW7, KIT, MUC4, ATM, CDH1, DDX11, DDX12, DSPP, EPPK1, FAM186A, GNAS, HRNR, KRTAP4-11, MAP2K4, MLL3, NRAS, RB1, SMAD4, TTN, ABCC9, ACVR1B, ADAM29, ADAMTS19, AGAP10, AKT1, AMBN, AMPD2, ANKRD30A, ANKRD40, APOBR, AR, BIRC6, BMP2, BRAT1, BTNL8, C12orf4, C1QTNF7, C20orf186, CAPRIN2, CBWD1, CCDC30, CCDC93, CD5L, CDC27, CDC42BPA, CDH9, CDKN2A, CHD8, CHEK2, CHRNA9, CIZ1, CLSPN, CNTN6, COL14A1, CREBBP, CROCC, CTSF, CYP1A2, DCLK1, DHDDS, DHX32, DKK2, DLEC1, DNAH14, DNAH5, DNAH9, DNASE1L3, DUSP16, DYNC2H1, ECT2, EFHB, RRN3P2, TRIM49B, TUBB8P5, EPHA7, ERBB3, ERCC6, FAM21A, FAM21C, FCGBP, FGFR2, FLG2, FLT1, FOLR2, FRYL, FSCB, GAB1, GABRA4, GABRP, GH2, GOLGA6L1, GPHB5, GPR32, GPX5, GTF3C3, HECW1, HIST1H3B, HLA-A, HRAS, HS3ST1, HS6ST1, HSPD1, IDH1, JAK2, KDM5B, KIAA0528, KRT15, KRT38, KRTAP21-1, KRTAP4-5, KRTAP4-7, KRTAP5-4, KRTAP5-5, LAMA4, LATS1, LMF1, LPAR4, LPPR4, LRRFIP1, LUM, LYST, MAP2K1, MARCH1, MARCO, MB21D2, MEGF10, MMP16, MORC1, MRE11A, MTMR3, MUC12, MUC17, MUC2, MUC20, NBPf10, NBPf20, NEK1, NFE2L2, NLRP4, NOTCH2, NRK, NUP93, OBSCN, OR11H1, OR2B11, OR2M4, OR4Q3, OR5D13, OR8I2, OXSM, PIK3R1, PPP2R5C, PRAME, PRF1, PRG4, PRPF19, PTH2, PTPRC, PTPRJ, RAC1, RAD50, RBM12, RGPd3, RGS22, ROR1, RP11-671M22.1, RP13-996F3.4, RP1L1, RSBN1L, RYR3, SAMD3, SCN3A, SEC31A, SF1, SF3B1, SLC25A2, SLC44A1, SLC4A11, SMAD2, SPTA1, ST6GAL2, STK11, SZT2, TAF1L, TAX1BP1, TBP, TGFBI, TIF1, TMEM14B, TMEM74, TPTE, TRAPPC8, TRPS1, TXNDC6, USP32, UTP20, VASN, VPS72, WASH3P, WWTR1, XPO1, ZFHx4, ZMIZ1, ZNF167, ZNF436, ZNF492, ZNF598, ZRSR2, and combinations thereof (Su *et al.*, J Mol Diagn 2011, 13:74–84; DOI:10.1016/j.jmoldx.2010.11.010; and Abaan *et al.*, "The Exomes of the NCI-60 Panel: A Genomic Resource for Cancer Biology and Systems Pharmacology",

Cancer Research, July 15, 2013, which are each hereby incorporated by reference in its entirety). In some embodiments, the duplication is a chromosome 1p (“Chr1p”) duplication associated with breast cancer. In some embodiments, one or more polymorphisms or mutations are in BRAF, such as the V600E mutation. In some embodiments, one or more polymorphisms or mutations are in K-ras. In some embodiments, there is a combination of one or more polymorphisms or mutations in K-ras and APC. In some embodiments, there is a combination of one or more polymorphisms or mutations in K-ras and p53. In some embodiments, there is a combination of one or more polymorphisms or mutations in APC and p53. In some embodiments, there is a combination of one or more polymorphisms or mutations in K-ras, APC, and p53. In some embodiments, there is a combination of one or more polymorphisms or mutations in K-ras and EGFR. Exemplary polymorphisms or mutations are in one or more of the following microRNAs: miR-15a, miR-16-1, miR-23a, miR-23b, miR-24-1, miR-24-2, miR-27a, miR-27b, miR-29b-2, miR-29c, miR-146, miR-155, miR-221, miR-222, and miR-223 (Calin et al. “A microRNA signature associated with prognosis and progression in chronic lymphocytic leukemia.” *N Engl J Med* 353:1793– 801, 2005, which is hereby incorporated by reference in its entirety).

[00341] In some embodiments, the deletion is a deletion of at least 0.01 kb, 0.1 kb, 1 kb, 10 kb, 100 kb, 1 mb, 2 mb, 3 mb, 5 mb, 10 mb, 15 mb, 20 mb, 30 mb, or 40 mb. In some embodiments, the deletion is a deletion of between 1 kb to 40 mb, such as between 1 kb to 100 kb, 100 kb to 1 mb, 1 to 5 mb, 5 to 10 mb, 10 to 15 mb, 15 to 20 mb, 20 to 25 mb, 25 to 30 mb, or 30 to 40 mb, inclusive.

[00342] In some embodiments, the duplication is a duplication of at least 0.01 kb, 0.1 kb, 1 kb, 10 kb, 100 kb, 1 mb, 2 mb, 3 mb, 5 mb, 10 mb, 15 mb, 20 mb, 30 mb, or 40 mb. In some embodiments, the duplication is a duplication of between 1 kb to 40 mb, such as between 1 kb to 100 kb, 100 kb to 1 mb, 1 to 5 mb, 5 to 10 mb, 10 to 15 mb, 15 to 20 mb, 20 to 25 mb, 25 to 30 mb, or 30 to 40 mb, inclusive.

[00343] In some embodiments, the tandem repeat is a repeat of between 2 and 60 nucleotides, such as 2 to 6, 7 to 10, 10 to 20, 20 to 30, 30 to 40, 40 to 50, or 50 to 60 nucleotides, inclusive. In some embodiments, the tandem repeat is a repeat of 2 nucleotides (dinucleotide repeat). In some embodiments, the tandem repeat is a repeat of 3 nucleotides (trinucleotide repeat).

[00344] In some embodiments, the polymorphism or mutation is prognostic. Exemplary prognostic mutations include K-ras mutations, such as K-ras mutations that are indicators of post-operative disease recurrence in colorectal cancer (Ryan *et al.* "A prospective study of circulating mutant KRAS2 in the serum of patients with colorectal neoplasia: strong prognostic indicator in postoperative follow up," Gut 52:101-108, 2003; and Lecomte T *et al.* Detection of free-circulating tumor-associated DNA in plasma of colorectal cancer patients and its association with prognosis," Int J Cancer 100:542-548, 2002, which are each hereby incorporated by reference in its entirety).

[00345] In some embodiments, the polymorphism or mutation is associated with altered response to a particular treatment (such as increased or decreased efficacy or side-effects). Examples include K-ras mutations are associated with decreased response to EGFR-based treatments in non-small cell lung cancer (Wang *et al.* "Potential clinical significance of a plasma-based KRAS mutation analysis in patients with advanced non-small cell lung cancer," Clin Canc Res 16:1324-1330, 2010, which is hereby incorporated by reference in its entirety).

[00346] K-ras is an oncogene that is activated in many cancers. Exemplary K-ras mutations are mutations in codons 12, 13, and 61. K-ras cfDNA mutations have been identified in pancreatic, lung, colorectal, bladder, and gastric cancers (Fleischhacker & Schmidt "Circulating nucleic acids (CNAs) and cancer – a survey," Biochim Biophys Acta 1775:181-232, 2007, which is hereby incorporated by reference in its entirety).

[00347] p53 is a tumor suppressor that is mutated in many cancers and contributes to tumor progression (Levine & Oren "The first 30 years of p53: growing ever more complex. Nature Rev Cancer," 9:749–758, 2009, which is hereby incorporated by reference in its entirety). Many different codons can be mutated, such as Ser249. p53 cfDNA mutations have been identified in breast, lung, ovarian, bladder, gastric, pancreatic, colorectal, bowel, and hepatocellular cancers (Fleischhacker & Schmidt "Circulating nucleic acids (CNAs) and cancer – a survey," Biochim Biophys Acta 1775:181-232, 2007, which is hereby incorporated by reference in its entirety).

[00348] BRAF is an oncogene downstream of Ras. BRAF mutations have been identified in glial neoplasm, melanoma, thyroid, and lung cancers (Dias-Santagata *et al.* BRAF V600E mutations are common in pleomorphic xanthoastrocytoma: diagnostic and therapeutic implications. PLOS ONE 2011;6:e17948, 2011; Shinozaki *et al.* Utility of circulating B-Raf DNA mutation in serum for monitoring melanoma patients receiving biochemotherapy. Clin

Canc Res 13:2068-2074, 2007; and Board *et al.* Detection of BRAF mutations in the tumor and serum of patients enrolled in the AZD6244 (ARRY-142886) advanced melanoma phase II study. Brit J Canc 2009;101:1724-1730, which are each hereby incorporated by reference in its entirety). The BRAF V600E mutation occurs, *e.g.*, in melanoma tumors, and is more common in advanced stages. The V600E mutation has been detected in cfDNA.

[00349] EGFR contributes to cell proliferation and is misregulated in many cancers (Downward J. Targeting RAS signalling pathways in cancer therapy. Nature Rev Cancer 3:11–22, 2003; and Levine & Oren “The first 30 years of p53: growing ever more complex. Nature Rev Cancer,” 9:749–758, 2009, which is hereby incorporated by reference in its entirety). Exemplary EGFR mutations include those in exons 18-21, which have been identified in lung cancer patients. EGFR cfDNA mutations have been identified in lung cancer patients (Jia *et al.* “Prediction of epidermal growth factor receptor mutations in the plasma/pleural effusion to efficacy of gefitinib treatment in advanced non-small cell lung cancer,” J Canc Res Clin Oncol 2010;136:1341-1347, 2010, which is hereby incorporated by reference in its entirety).

[00350] Exemplary polymorphisms or mutations associated with breast cancer include LOH at microsatellites (Kohler *et al.* “Levels of plasma circulating cell free nuclear and mitochondrial DNA as potential biomarkers for breast tumors,” Mol Cancer 8:doi:10.1186/1476-4598-8-105, 2009, which is hereby incorporated by reference in its entirety), p53 mutations (such as mutations in exons 5-8)(Garcia *et al.* “Extracellular tumor DNA in plasma and overall survival in breast cancer patients,” Genes, Chromosomes & Cancer 45:692-701, 2006, which is hereby incorporated by reference in its entirety), HER2 (Sorensen *et al.* “Circulating *HER2* DNA after trastuzumab treatment predicts survival and response in breast cancer,” Anticancer Res30:2463-2468, 2010, which is hereby incorporated by reference in its entirety), PIK3CA, MED1, and GAS6 polymorphisms or mutations (Murtaza *et al.* “Non-invasive analysis of acquired resistance to cancer therapy by sequencing of plasma DNA,” Nature 2013;doi:10.1038/nature12065, 2013, which is hereby incorporated by reference in its entirety). Increased cfDNA levels and LOH are associated with decreased overall and disease-free survival. p53 mutations (exons 5-8) are associated with decreased overall survival. Decreased circulating HER2 cfDNA levels are associated with a better response to HER2-targeted treatment in HER2-positive breast tumor subjects. An activating mutation in PIK3CA, a truncation of MED1, and a splicing mutation in GAS6 result in resistance to treatment.

[00351] Exemplary polymorphisms or mutations associated with colorectal cancer include p53, APC, K-ras, and thymidylate synthase mutations and p16 gene methylation (Wang *et al.* “Molecular detection of APC, K-ras, and p53 mutations in the serum of colorectal cancer patients as circulating biomarkers,” World J Surg 28:721-726, 2004; Ryan *et al.* “A prospective study of circulating mutant KRAS2 in the serum of patients with colorectal neoplasia: strong prognostic indicator in postoperative follow up,” Gut 52:101-108, 2003; Lecomte *et al.* “Detection of free-circulating tumor-associated DNA in plasma of colorectal cancer patients and its association with prognosis,” Int J Cancer 100:542-548, 2002; Schwarzenbach *et al.* “Molecular analysis of the polymorphisms of thymidylate synthase on cell-free circulating DNA in blood of patients with advanced colorectal carcinoma,” Int J Cancer 127:881-888, 2009, which are each hereby incorporated by reference in its entirety). Post-operative detection of K-ras mutations in serum is a strong predictor of disease recurrence. Detection of K-ras mutations and p16 gene methylation are associated with decreased survival and increased disease recurrence. Detection of K-ras, APC, and/or p53 mutations is associated with recurrence and/or metastases. Polymorphisms (including LOH, SNPs, variable number tandem repeats, and deletion) in the thymidylate synthase (the target of fluoropyrimidine-based chemotherapies) gene using cfDNA may be associated with treatment response.

[00352] Exemplary polymorphisms or mutations associated with lung cancer (such as non-small cell lung cancer) include K-ras (such as mutations in codon 12) and EGFR mutations. Exemplary prognostic mutations include EGFR mutations (exon 19 deletion or exon 21 mutation) associated with increased overall and progression-free survival and K-ras mutations (in codons 12 and 13) are associated with decreased progression-free survival (Jian *et al.* “Prediction of epidermal growth factor receptor mutations in the plasma/pleural effusion to efficacy of gefitinib treatment in advanced non-small cell lung cancer,” J Canc Res Clin Oncol 136:1341-1347, 2010; Wang *et al.* “Potential clinical significance of a plasma-based KRAS mutation analysis in patients with advanced non-small cell lung cancer,” Clin Canc Res 16:1324-1330, 2010, which are each hereby incorporated by reference in its entirety). Exemplary polymorphisms or mutations indicative of response to treatment include EGFR mutations (exon 19 deletion or exon 21 mutation) that improve response to treatment and K-ras mutations (codons 12 and 13) that decrease the response to treatment. A resistance-conferring mutation in EFGR has been identified (Murtaza *et al.* “Non-invasive analysis of acquired resistance to

cancer therapy by sequencing of plasma DNA,” Nature doi:10.1038/nature12065, 2013, which is hereby incorporated by reference in its entirety).

[00353] Exemplary polymorphisms or mutations associated with melanoma (such as uveal melanoma) include those in GNAQ, GNA11, BRAF, and p53. Exemplary GNAQ and GNA11 mutations include R183 and Q209 mutations. Q209 mutations in GNAQ or GNA11 are associated with metastases to bone. BRAF V600E mutations can be detected in patients with metastatic/advanced stage melanoma. BRAF V600E is an indicator of invasive melanoma. The presence of the BRAF V600E mutation after chemotherapy is associated with a non-response to the treatment

[00354] Exemplary polymorphisms or mutations associated with pancreatic carcinomas include those in K-ras and p53 (such as p53 Ser249). p53 Ser249 is also associated with hepatitis B infection and hepatocellular carcinoma, as well as ovarian cancer, and non-Hodgkin’s lymphoma.

[00355] Even polymorphisms or mutations that are present in low frequency in a sample can be detected with the methods of the invention. For example, a polymorphism or mutation that is present at a frequency of 1 in a million can be observed 10 times by performing 10 million sequencing reads. If desired, the number of sequencing reads can be altered depending of the level of sensitivity desired. In some embodiments, a sample is re-analyzed or another sample from a subject is analyzed using a greater number of sequencing reads to improve the sensitivity. For example, if no or only a small number (such as 1, 2, 3, 4, or 5) polymorphisms or mutations that are associated with cancer or an increased risk for cancer are detected, the sample is re-analyzed or another sample is tested.

[00356] In some embodiments, multiple polymorphisms or mutations are required for cancer or for metastatic cancer. In such cases, screening for multiple polymorphisms or mutations improves the ability to accurately diagnose cancer or metastatic cancer. In some embodiments when a subject has a subset of multiple polymorphisms or mutations that are required for cancer or for metastatic cancer, the subject can be re-screened later to see if the subject acquires additional mutations.

[00357] In some embodiments in which multiple polymorphisms or mutations are required for cancer or for metastatic cancer, the frequency of each polymorphism or mutation can be compared to see if they occur at similar frequencies. For example, if two mutations required for

cancer (denoted “A” and “B”), some cells will have none, some cells with A, some with B, and some with A and B. If A and B are observed at similar frequencies, the subject is more likely to have some cells with both A and B. If observer A and B at dissimilar frequencies, the subject is more likely to have different cell populations.

[00358] In some embodiments in which multiple polymorphisms or mutations are required for cancer or for metastatic cancer, the number or identity of such polymorphisms or mutations that are present in the subject can be used to predict how likely or soon the subject is likely to have the disease or disorder. In some embodiments in which polymorphisms or mutations tend to occur in a certain order, the subject may be periodically tested to see if the subject has acquired the other polymorphisms or mutations.

Exemplary Nucleic Acid Alterations

[00359] In some embodiments, there is a change to the integrity of RNA or DNA (such as a change in the size of fragmented cfRNA or cfDNA or a change in nucleosome composition) that is associated with a disease or disorder such as cancer, or an increased risk for a disease or disorder such as cancer. In some embodiments, there is a change in the methylation pattern RNA or DNA that is associated with a disease or disorder such as cancer, or an increased risk for with a disease or disorder such as cancer (*e.g.*, hypermethylation of tumor suppressor genes). For example, methylation of the CpG islands in the promoter region of tumor-suppressor genes has been suggested to trigger local gene silencing. Aberrant methylation of the p16 tumor suppressor gene occurs in subjects with liver, lung, and breast cancer. Other frequently methylated tumor suppressor genes, including APC, Ras association domain family protein 1A (RASSF1A), glutathione S-transferase P1 (GSTP1), and DAPK, have been detected in various type of cancers, for example nasopharyngeal carcinoma, colorectal cancer, lung cancer, oesophageal cancer, prostate cancer, bladder cancer, melanoma, and acute leukemia. Methylation of certain tumor-suppressor genes, such as p16, has been described as an early event in cancer formation, and thus is useful for early cancer screening.

[00360] In some embodiments, bisulphite conversion or a non-bisulphite based strategy using methylation sensitive restriction enzyme digestion is used to determine the methylation pattern (Hung *et al.*, J Clin Pathol 62:308–313, 2009, which is hereby incorporated by reference in its entirety). On bisulphite conversion, methylated cytosines remain as cytosines while

unmethylated cytosines are converted to uracils. Methylation-sensitive restriction enzymes (*e.g.*, BstUI) cleaves unmethylated DNA sequences at specific recognition sites (*e.g.*, 5'-CG $\vee$ CG-3' for BstUI), while methylated sequences remain intact. In some embodiments, the intact methylated sequences are detected. In some embodiments, stem-loop primers are used to selectively amplify restriction enzyme-digested unmethylated fragments without co-amplifying the non-enzyme-digested methylated DNA.

Exemplary Changes in mRNA Splicing

[00361] In some embodiments, a change in mRNA splicing is associated with a disease or disorder such as cancer, or an increased risk for a disease or disorder such as cancer. In some embodiments, the change in mRNA splicing is in one or more of the following nucleic acids associated with cancer or an increased risk for cancer: DNMT3B, BRCA1, KLF6, Ron, or Gemin5. In some embodiments, the detected mRNA splice variant is associated with a disease or disorder, such as cancer. In some embodiments, multiple mRNA splice variants are produced by healthy cells (such as non-cancerous cells), but a change in the relative amounts of the mRNA splice variants is associated with a disease or disorder, such as cancer. In some embodiments, the change in mRNA splicing is due to a change in the mRNA sequence (such as a mutation in a splice site), a change in splicing factor levels, a change in the amount of available splicing factor (such as a decrease in the amount of available splicing factor due to the binding of a splicing factor to a repeat), altered splicing regulation, or the tumor microenvironment.

[00362] The splicing reaction is carried out by a multi-protein/RNA complex called the spliceosome (Fackenthal and Godley, Disease Models & Mechanisms 1: 37-42, 2008, doi:10.1242/dmm.000331, which is hereby incorporated by reference in its entirety). The spliceosome recognizes intron-exon boundaries and removes intervening introns via two transesterification reactions that result in ligation of two adjacent exons. The fidelity of this reaction must be exquisite, because if the ligation occurs incorrectly, normal protein-encoding potential may be compromised. For example, in cases where exon-skipping preserves the reading frame of the triplet codons specifying the identity and order of amino acids during translation, the alternatively spliced mRNA may specify a protein that lacks crucial amino acid residues. More commonly, exon-skipping will disrupt the translational reading frame, resulting in premature stop codons. These mRNAs are typically degraded by at least 90% through a

process known as nonsense-mediated mRNA degradation, which reduces the likelihood that such defective messages will accumulate to generate truncated protein products. If mis-spliced mRNAs escape this pathway, then truncated, mutated, or unstable proteins are produced.

[00363] Alternative splicing is a means of expressing several or many different transcripts from the same genomic DNA and results from the inclusion of a subset of the available exons for a particular protein. By excluding one or more exons, certain protein domains may be lost from the encoded protein, which can result in protein function loss or gain. Several types of alternative splicing have been described: exon skipping; alternative 5' or 3' splice sites; mutually exclusive exons; and, much more rarely, intron retention. Others have compared the amount of alternative splicing in cancer versus normal cells using a bioinformatic approach and determined that cancers exhibit lower levels of alternative splicing than normal cells. Furthermore, the distribution of the types of alternative splicing events differed in cancer versus normal cells. Cancer cells demonstrated less exon skipping, but more alternative 5' and 3' splice site selection and intron retention than normal cells. When the phenomenon of exonization (the use of sequences as exons that are used predominantly by other tissues as introns) was examined, genes associated with exonization in cancer cells were preferentially associated with mRNA processing, indicating a direct link between cancer cells and the generation of aberrant mRNA splice forms.

Exemplary Changes in DNA or RNA Levels

[00364] In some embodiments, there is a change in the total amount or concentration of one or more types of DNA (such as cfDNA cf mDNA, cf nDNA, cellular DNA, or mitochondrial DNA) or RNA (cfRNA, cellular RNA, cytoplasmic RNA, coding cytoplasmic RNA, non-coding cytoplasmic RNA, mRNA, miRNA, mitochondrial RNA, rRNA, or tRNA). In some embodiments, there is a change in the amount or concentration of one or more specific DNA (such as cfDNA cf mDNA, cf nDNA, cellular DNA, or mitochondrial DNA) or RNA (cfRNA, cellular RNA, cytoplasmic RNA, coding cytoplasmic RNA, non-coding cytoplasmic RNA, mRNA, miRNA, mitochondrial RNA, rRNA, or tRNA) molecules. In some embodiments, one allele is expressed more than another allele of a locus of interest. Exemplary miRNAs are short 20–22 nucleotide RNA molecules that regulate the expression of a gene.

[00365] In some embodiments, an increase in the total amount or concentration of cfDNA or cfRNA is associated with a disease or disorder such as cancer, or an increased risk for a disease or disorder such as cancer. In some embodiments, the total concentration of a type of DNA (such as cfDNA cf mRNA, cf nDNA, cellular DNA, or mitochondrial DNA) or RNA (cfRNA, cellular RNA, cytoplasmic RNA, coding cytoplasmic RNA, non-coding cytoplasmic RNA, mRNA, miRNA, mitochondrial RNA, rRNA, or tRNA) increases by at least 2, 3, 4, 5, 6, 7, 8, 9, 10-fold, or more compared to the total concentration of that type of DNA or RNA in healthy (such as non-cancerous) subjects. In some embodiments, a total concentration of cfDNA between 75 to 100 ng/mL, 100 to 150 ng/mL, 150 to 200 ng/mL, 200 to 300 ng/mL, 300 to 400 ng/mL, 400 to 600 ng/mL, 600 to 800 ng/mL, 800 to 1,000 ng/mL, inclusive, or a total concentration of cfDNA of more than 100 ng/mL, such as more than 200, 300, 400, 500, 600, 700, 800, 900, or 1,000 ng/mL is indicative of cancer, an increased risk for cancer, an increased risk of a tumor being malignant rather than benign, a decreased probability of the cancer going into remission, or a worse prognosis for the cancer. In some embodiments, the amount of a type of DNA (such as cfDNA cf mRNA, cf nDNA, cellular DNA, or mitochondrial DNA) or RNA (cfRNA, cellular RNA, cytoplasmic RNA, coding cytoplasmic RNA, non-coding cytoplasmic RNA, mRNA, miRNA, mitochondrial RNA, rRNA, or tRNA) having one or more polymorphisms/mutations (such as deletions or duplications) associated with a disease or disorder such as cancer or an increased risk for a disease or disorder such as cancer is at least 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 16, 18, 20, or 25% of the total amount of that type of DNA or RNA. In some embodiments, at least 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 16, 18, 20, or 25% of the total amount of a type of DNA (such as cfDNA cf mRNA, cf nDNA, cellular DNA, or mitochondrial DNA) or RNA (cfRNA, cellular RNA, cytoplasmic RNA, coding cytoplasmic RNA, non-coding cytoplasmic RNA, mRNA, miRNA, mitochondrial RNA, rRNA, or tRNA) has a particular polymorphism or mutation (such as a deletion or duplication) associated with a disease or disorder such as cancer or an increased risk for a disease or disorder such as cancer.

[00366] In some embodiments, the cfDNA is encapsulated. In some embodiments, the cfDNA is not encapsulated.

Exemplary Databases

[00367] The invention also features databases containing one or more results from a method of the invention. For example, the database may include records with any of the following information for one or more subjects: any polymorphisms/mutations (such as CNVs) identified, any known association of the polymorphisms/mutations with a disease or disorder or an increased risk for a disease or disorder, effect of the polymorphisms/mutations on the expression or activity level of the encoded mRNA or protein, fraction of DNA, RNA, or cells associated with a disease or disorder (such as DNA, RNA, or cells having polymorphism/mutation associated with a disease or disorder) out of the total DNA, RNA, or cells in sample, source of sample used to identify the polymorphisms/mutations (such as a blood sample or sample from a particular tissue), number of diseased cells, results from later repeating the test (such as repeating the test to monitor the progression or remission of the disease or disorder), results of other tests for the disease or disorder, type of disease or disorder the subject was diagnosed with, treatment(s) administered, response to such treatment(s), side-effects of such treatment(s), symptoms (such as symptoms associated with the disease or disorder), length and number of remissions, length of survival (such as length of time from initial test until death or length of time from diagnosis until death), cause of death, and combinations thereof.

[00368] In some embodiments, the database includes records with any of the following information for one or more subjects: any polymorphisms/mutations identified, any known association of the polymorphisms/mutations with cancer or an increased risk for cancer, effect of the polymorphisms/mutations on the expression or activity level of the encoded mRNA or protein, fraction of cancerous DNA, RNA or cells out of the total DNA, RNA, or cells in sample, source of sample used to identify the polymorphisms/mutations (such as a blood sample or sample from a particular tissue), number of cancerous cells, size of tumor(s), results from later repeating the test (such as repeating the test to monitor the progression or remission of the cancer), results of other tests for cancer, type of cancer the subject was diagnosed with, treatment(s) administered, response to such treatment(s), side-effects of such treatment(s), symptoms (such as symptoms associated with cancer), length and number of remissions, length of survival (such as length of time from initial test until death or length of time from cancer diagnosis until death), cause of death, and combinations thereof. In some embodiments, the response to treatment includes any of the following: reducing or stabilizing the size of a tumor (*e.g.*, a benign or cancerous tumor), slowing or preventing an increase in the size of a tumor,

reducing or stabilizing the number of tumor cells, increasing the disease-free survival time between the disappearance of a tumor and its reappearance, preventing an initial or subsequent occurrence of a tumor, reducing or stabilizing an adverse symptom associated with a tumor, or combinations thereof. In some embodiments, the results from one or more other tests for a disease or disorder such as cancer are included, such as results from screening tests, medical imaging, or microscopic examination of a tissue sample.

[00369] In one such aspect, the invention features an electronic database including at least 5, 10, 10^2 , 10^3 , 10^4 , 10^5 , 10^6 , 10^7 , 10^8 or more records. In some embodiments, the database has records for at least 5, 10, 10^2 , 10^3 , 10^4 , 10^5 , 10^6 , 10^7 , 10^8 or more different subjects.

[00370] In another aspect, the invention features a computer including a database of the invention and a user interface. In some embodiments, the user interface is capable of displaying a portion or all of the information contained in one or more records. In some embodiments, the user interface is capable of displaying (i) one or more types of cancer that have been identified as containing a polymorphism or mutation whose record is stored in the computer, (ii) one or more polymorphisms or mutations that have been identified in a particular type of cancer whose record is stored in the computer, (iii) prognosis information for a particular type of cancer or a particular a polymorphism or mutation whose record is stored in the computer (iv) one or more compounds or other treatments useful for cancer with a polymorphism or mutation whose record is stored in the computer, (v) one or more compounds that modulate the expression or activity of an mRNA or protein whose record is stored in the computer, and (vi) one or more mRNA molecules or proteins whose expression or activity is modulated by a compound whose record is stored in the computer. The internal components of the computer typically include a processor coupled to a memory. The external components usually include a mass-storage device, *e.g.*, a hard disk drive; user input devices, *e.g.*, a keyboard and a mouse; a display, *e.g.*, a monitor; and optionally, a network link capable of connecting the computer system to other computers to allow sharing of data and processing tasks. Programs may be loaded into the memory of this system during operation.

[00371] In another aspect, the invention features a computer-implemented process that includes one or more steps of any of the methods of the invention.

Exemplary Risk Factors

[00372] In some embodiments, the subject is also evaluated for one or more risk factors for a disease or disorder, such as cancer. Exemplary risk factors include family history for the disease or disorder, lifestyle (such as smoking and exposure to carcinogens) and the level of one or more hormones or serum proteins (such as alpha-fetoprotein (AFP) in liver cancer, carcinoembryonic antigen (CEA) in colorectal cancer, or prostate-specific antigen (PSA) in prostate cancer). In some embodiments, the size and/or number of tumors is measured and use in determining a subject's prognosis or selecting a treatment for the subject.

Exemplary Screening Methods

[00373] If desired, the presence or absence of a disease or disorder such as cancer can be confirmed, or the disease or disorder such as cancer can be classified using any standard method. For example, a disease or disorder such as cancer can be detected in a number of ways, including the presence of certain signs and symptoms, screening tests, or medical imaging. Once a possible cancer is detected, it may be diagnosed by microscopic examination of a tissue sample.

[00374] In some embodiments, a subject diagnosed undergoes repeat testing using a method of the invention or known testing for the disease or disorder at multiple time points to monitor the progression of the disease or disorder or the remission or reoccurrence of the disease or disorder.

Exemplary Cancers

[00375] Exemplary cancers that can be diagnosed, prognosed, stabilized, treated, or prevented using any of the methods of the invention include solid tumors, carcinomas, sarcomas, lymphomas, leukemias, germ cell tumors, or blastomas. In various embodiments, the cancer is an acute lymphoblastic leukemia, acute myeloid leukemia, adrenocortical carcinoma, AIDS-related cancer, AIDS-related lymphoma, anal cancer, appendix cancer, astrocytoma (such as childhood cerebellar or cerebral astrocytoma), basal-cell carcinoma, bile duct cancer (such as extrahepatic bile duct cancer) bladder cancer, bone tumor (such as osteosarcoma or malignant fibrous histiocytoma), brainstem glioma, brain cancer (such as cerebellar astrocytoma, cerebral astrocytoma/malignant glioma, ependymo, medulloblastoma, supratentorial primitive neuroectodermal tumors, or visual pathway and hypothalamic glioma), breast cancer, bronchial adenoma or carcinoid, burkitt's lymphoma, carcinoid tumor (such as a childhood or gastrointestinal carcinoid tumor), carcinoma central nervous system lymphoma, cerebellar

astrocytoma or malignant glioma (such as childhood cerebellar astrocytoma or malignant glioma), cervical cancer, childhood cancer, chronic lymphocytic leukemia, chronic myelogenous leukemia, chronic myeloproliferative disorders, colon cancer, cutaneous t-cell lymphoma, desmoplastic small round cell tumor, endometrial cancer, ependymoma, esophageal cancer, ewing's sarcoma, tumor in the ewing family of tumors, extracranial germ cell tumor (such as a childhood extracranial germ cell tumor), extragonadal germ cell tumor, eye cancer (such as intraocular melanoma or retinoblastoma eye cancer), gallbladder cancer, gastric cancer, gastrointestinal carcinoid tumor, gastrointestinal stromal tumor, germ cell tumor (such as extracranial, extragonadal, or ovarian germ cell tumor), gestational trophoblastic tumor, glioma (such as brain stem, childhood cerebral astrocytoma, or childhood visual pathway and hypothalamic glioma), gastric carcinoid, hairy cell leukemia, head and neck cancer, heart cancer, hepatocellular (liver) cancer, hodgkin lymphoma, hypopharyngeal cancer, hypothalamic and visual pathway glioma (such as childhood visual pathway glioma), islet cell carcinoma (such as endocrine or pancreas islet cell carcinoma), kaposi sarcoma, kidney cancer, laryngeal cancer, leukemia (such as acute lymphoblastic, acute myeloid, chronic lymphocytic, chronic myelogenous, or hairy cell leukemia), lip or oral cavity cancer, liposarcoma, liver cancer (such as non-small cell or small cell lung cancer), lymphoma (such as AIDS-related, burkitt, cutaneous T cell, Hodgkin, non-hodgkin, or central nervous system lymphoma), macroglobulinemia (such as waldenström macroglobulinemia, malignant fibrous histiocytoma of bone or osteosarcoma, medulloblastoma (such as childhood medulloblastoma), melanoma, merkel cell carcinoma, mesothelioma (such as adult or childhood mesothelioma), metastatic squamous neck cancer with occult, mouth cancer, multiple endocrine neoplasia syndrome (such as childhood multiple endocrine neoplasia syndrome), multiple myeloma or plasma cell neoplasm. mycosis fungoides, myelodysplastic syndrome, myelodysplastic or myeloproliferative disease, myelogenous leukemia (such as chronic myelogenous leukemia), myeloid leukemia (such as adult acute or childhood acute myeloid leukemia), myeloproliferative disorder (such as chronic myeloproliferative disorder), nasal cavity or paranasal sinus cancer, nasopharyngeal carcinoma, neuroblastoma, oral cancer, oropharyngeal cancer, osteosarcoma or malignant fibrous histiocytoma of bone, ovarian cancer, ovarian epithelial cancer, ovarian germ cell tumor, ovarian low malignant potential tumor, pancreatic cancer (such as islet cell pancreatic cancer), paranasal sinus or nasal cavity cancer, parathyroid cancer, penile cancer, pharyngeal cancer,

pheochromocytoma, pineal astrocytoma, pineal germinoma, pineoblastoma or supratentorial primitive neuroectodermal tumor (such as childhood pineoblastoma or supratentorial primitive neuroectodermal tumor), pituitary adenoma, plasma cell neoplasia, pleuropulmonary blastoma, primary central nervous system lymphoma, prostate cancer, rectal cancer, renal cell carcinoma, renal pelvis or ureter cancer (such as renal pelvis or ureter transitional cell cancer, retinoblastoma, rhabdomyosarcoma (such as childhood rhabdomyosarcoma), salivary gland cancer, sarcoma (such as sarcoma in the ewing family of tumors, Kaposi, soft tissue, or uterine sarcoma), sézary syndrome, skin cancer (such as nonmelanoma, melanoma, or merkel cell skin cancer), small intestine cancer, squamous cell carcinoma, supratentorial primitive neuroectodermal tumor (such as childhood supratentorial primitive neuroectodermal tumor), T-cell lymphoma (such as cutaneous T-cell lymphoma), testicular cancer, throat cancer, thymoma (such as childhood thymoma), thymoma or thymic carcinoma, thyroid cancer (such as childhood thyroid cancer), trophoblastic tumor (such as gestational trophoblastic tumor), unknown primary site carcinoma (such as adult or childhood unknown primary site carcinoma), urethral cancer (such as endometrial uterine cancer), uterine sarcoma, vaginal cancer, visual pathway or hypothalamic glioma (such as childhood visual pathway or hypothalamic glioma), vulvar cancer, waldenström macroglobulinemia, or wilms tumor (such as childhood wilms tumor). In various embodiments, the cancer has metastasized or has not metastasized.

[00376] The cancer may or may not be a hormone related or dependent cancer (*e.g.*, an estrogen or androgen related cancer). Benign tumors or malignant tumors may be diagnosed, prognosed, stabilized, treated, or prevented using the methods and/or compositions of the present invention.

[00377] In some embodiments, the subject has a cancer syndrome. A cancer syndrome is a genetic disorder in which genetic mutations in one or more genes predispose the affected individuals to the development of cancers and may also cause the early onset of these cancers. Cancer syndromes often show not only a high lifetime risk of developing cancer, but also the development of multiple independent primary tumors. Many of these syndromes are caused by mutations in tumor suppressor genes, genes that are involved in protecting the cell from turning cancerous. Other genes that may be affected are DNA repair genes, oncogenes and genes involved in the production of blood vessels (angiogenesis). Common examples of inherited cancer syndromes are hereditary breast-ovarian cancer syndrome and hereditary non-polyposis colon cancer (Lynch syndrome).

[00378] In some embodiments, a subject with one or more polymorphisms or mutations in K-ras, p53, BRA, EGFR, or HER2 is administered a treatment that targets K-ras, p53, BRA, EGFR, or HER2, respectively.

[00379] The methods of the invention can be generally applied to the treatment of malignant or benign tumors of any cell, tissue, or organ type.

Exemplary Treatments

[00380] If desired, any treatment for stabilizing, treating, or preventing a disease or disorder such as cancer or an increased risk for a disease or disorder such as cancer can be administered to a subject (*e.g.*, a subject identified as having cancer or an increased risk for cancer using any of the methods of the invention). In various embodiments, the treatment is a known treatment or combination of treatments for a disease or disorder such as cancer, such as cytotoxic agents, targeted therapy, immunotherapy, hormonal therapy, radiation therapy, surgical removal of cancerous cells or cells likely to become cancerous, stem cell transplantation, bone marrow transplantation, photodynamic therapy, palliative treatment, or a combination thereof. In some embodiments, a treatment (such as a preventative medication) is used to prevent, delay, or reduce the severity of a disease or disorder such as cancer in a subject at increased risk for a disease or disorder such as cancer.

[00381] In some embodiments, the targeted therapy is a treatment that targets the cancer's specific genes, proteins, or the tissue environment that contributes to cancer growth and survival. This type of treatment blocks the growth and spread of cancer cells while limiting damage to normal cells, usually leading to fewer side effects than other cancer medications.

[00382] One of the more successful approaches has been to target angiogenesis, the new blood vessel growth around a tumor. Targeted therapies such as bevacizumab (Avastin), lenalidomide (Revlimid), sorafenib (Nexavar), sunitinib (Sutent), and thalidomide (Thalomid) interfere with angiogenesis. Another example is the use of a treatment that targets HER2, such as trastuzumab or lapatinib, for cancers that overexpress HER2 (such as some breast cancers). In some embodiments, a monoclonal antibody is used to block a specific target on the outside of cancer cells. Examples include alemtuzumab (Campath-1H), bevacizumab, cetuximab (Erbix), panitumumab (Vectibix), pertuzumab (Omnitarg), rituximab (Rituxan), and trastuzumab. In some embodiments, the monoclonal antibody tositumomab (Bexxar) is used to deliver radiation

to the tumor. In some embodiments, an oral small molecule inhibits a cancer process inside of a cancer cell. Examples include dasatinib (Sprycel), erlotinib (Tarceva), gefitinib (Iressa), imatinib (Gleevec), lapatinib (Tykerb), nilotinib (Tasigna), sorafenib, sunitinib, and temsirolimus (Torisel). In some embodiments, a proteasome inhibitor (such as the multiple myeloma drug, bortezomib (Velcade)) interferes with specialized proteins called enzymes that break down other proteins in the cell.

[00383] In some embodiments, immunotherapy is designed to boost the body's natural defenses to fight the cancer. Exemplary types of immunotherapy use materials made either by the body or in a laboratory to bolster, target, or restore immune system function.

[00384] In some embodiments, hormonal therapy treats cancer by lowering the amounts of hormones in the body. Several types of cancer, including some breast and prostate cancers, only grow and spread in the presence of natural chemicals in the body called hormones. In various embodiments, hormonal therapy is used to treat cancers of the prostate, breast, thyroid, and reproductive system.

[00385] In some embodiments, the treatment includes a stem cell transplant in which diseased bone marrow is replaced by highly specialized cells, called hematopoietic stem cells. Hematopoietic stem cells are found both in the bloodstream and in the bone marrow.

[00386] In some embodiments, the treatment includes photodynamic therapy, which uses special drugs, called photosensitizing agents, along with light to kill cancer cells. The drugs work after they have been activated by certain kinds of light.

[00387] In some embodiments, the treatment includes surgical removal of cancerous cells or cells likely to become cancerous. For example, a woman with a breast cancer susceptibility gene mutation (*BRCA1* or *BRCA2* gene mutation) may reduce her risk of breast and ovarian cancer with a risk reducing salpingo-oophorectomy (removal of the fallopian tubes and ovaries) and/or a risk reducing bilateral mastectomy (removal of both breasts). Lasers, which are very powerful, precise beams of light, can be used instead of blades (scalpels) for very careful surgical work, including treating some cancers.

[00388] In addition to treatment to slow, stop, or eliminate the cancer (also called disease-directed treatment), an important part of cancer care is relieving a subject's symptoms and side effects, such as pain and nausea. It includes supporting the subject with physical, emotional, and

social needs, an approach called palliative or supportive care. People often receive disease-directed therapy and treatment to ease symptoms at the same time.

[00389] Exemplary treatments include actinomycin D, adcetris, Adriamycin, aldesleukin, alemtuzumab, alimta, amsidine, amsacrine, anastrozole, aredia, arimidex, aromasin, asparaginase, avastin, bevacizumab, bicalutamide, bleomycin, bondronat, bonefos, bortezomib, busilvex, busulphan, campto, capecitabine, carboplatin, carmustine, casodex, cetuximab, chimax, chlorambucil, cimetidine, cisplatin, cladribine, clodronate, clofarabine, crisantaspase, cyclophosphamide, cyproterone acetate, cyprostat, cytarabine, cytoxan, dacarbozine, dactinomycin, dasatinib, daunorubicin, dexamethasone, diethylstilbestrol, docetaxel, doxorubicin, drogenil, emcyt, epirubicin, eposin, Erbitux, erlotinib, estracyte, estramustine, etopophos, etoposide, evoltra, exemestane, fareston, femara, filgrastim, fludara, fludarabine, fluorouracil, flutamide, gefinitib, gemcitabine, gemzar, gleevec, glivec. gonapeptyl depot, goserelin, halaven, herceptin, hycamptin, hydroxycarbamide, ibandronic acid, ibritumomab, idarubicin, ifosfomide, interferon, imatinib mesylate, iressa, irinotecan, jevtana, lanvis, lapatinib, letrozole, leukeran, leuprorelin, leustat, lomustine, mabcampath, mabthera, megace, megestrol, methotrexate, mitozantrone, mitomycin, mutulane, myleran, navelbine, neulasta, neupogen, nexavar, nipent, nolvadex D, novantron, oncovin, paclitaxel, pamidronate, PCV, pemetrexed, pentostatin, perjeta, procarbazine, provenge, prednisolone, prostrap, raltitrexed, rituximab, sprycel, sorafenib, soltamox, streptozocin, stilboestrol, stimuvax, sunitinib, sutent, tabloid, tagamet, tamofen, tamoxifen, tarceva, taxol, taxotere, tegafur with uracil, temodal, temozolomide, thalidomide, thioplex, thiotepa, tioguanine, tomudex, topotecan, toremifene, trastuzumab, tretinoin, treosulfan, triethylenethiophosphoramidate, triptorelin, tyverb, uftoral, velcade, vepesid, vesanoid, vincristine, vinorelbine, xalkori, xeloda, yervoy, zactima, zanosar, zavedos, zevelin, zoladex, zoledronate, zometa zoledronic acid, and zytiga.

[00390] For subjects that express both a mutant form (*e.g.*, a cancer-related form) and a wild-type form (*e.g.*, a form not associated with cancer) of an mRNA or protein, the therapy preferably inhibits the expression or activity of the mutant form by at least 2, 5, 10, or 20-fold more than it inhibits the expression or activity of the wild-type form. The simultaneous or sequential use of multiple therapeutic agents may greatly reduce the incidence of cancer and reduce the number of treated cancers that become resistant to therapy. In addition, therapeutic agents that are used as part of a combination therapy may require a lower dose to treat cancer

than the corresponding dose required when the therapeutic agents are used individually. The low dose of each compound in the combination therapy reduces the severity of potential adverse side-effects from the compounds.

[00391] In some embodiments, a subject identified as having an increased risk of cancer may (by the invention or any standard method), avoid specific risk factors, or make lifestyle changes to reduce any additional risk of cancer.

[00392] In some embodiments, the polymorphisms, mutations, risk factors, or any combination thereof are used to select a treatment regimen for the subject. In some embodiments, a larger dose or greater number of treatments is selected for a subject at greater risk of cancer or with a worse prognosis.

Other Compounds for Inclusion in Individual or Combination Therapies

[00393] If desired, additional compounds for stabilizing, treating, or preventing a disease or disorder such as cancer or an increased risk for a disease or disorder such as cancer may be identified from large libraries of both natural product or synthetic (or semi-synthetic) extracts or chemical libraries according to methods known in the art. Those skilled in the field of drug discovery and development will understand that the precise source of test extracts or compounds is not critical to the methods of the invention. Accordingly, virtually any number of chemical extracts or compounds can be screened for their effect on cells from a particular type of cancer or from a particular subject or screened for their effect on the activity or expression of cancer related molecules (such as cancer related molecules known to have altered activity or expression in a particular type of cancer). When a crude extract is found to modulate the activity or expression of a cancer related molecule, further fractionation of the positive lead extract may be performed to isolate chemical constituent responsible for the observed effect using methods known in the art.

Exemplary Assays and Animal Models for the Testing of Therapies

[00394] If desired, one or more of the treatment disclosed herein can be tested for their effect on a disease or disorder such as cancer using a cell line (such as a cell line with one or more of the mutations identified in the subject who has been diagnosed with cancer or an increased risk of cancer using the methods of the invention) or an animal model of the disease or disorder, such as

a SCID mouse model (Jain *et al.*, Tumor Models In Cancer Research, ed. Teicher, Humana Press Inc., Totowa, N.J., pp. 647-671, 2001, which is hereby incorporated by reference in its entirety). Additionally, there are numerous standard assays and animal models that can be used to determine the efficacy of particular therapies for stabilizing, treating, or preventing a disease or disorder such as cancer or an increased risk for a disease or disorder such as cancer. Therapies can also be tested in standard human clinical trials.

[00395] For the selection of a preferred therapy for a particular subject, compounds can be tested for their effect on the expression or activity on one or more genes that are mutated in the subject. For example, the ability of a compound to modulate the expression of particular mRNA molecules or proteins can be detected using standard Northern, Western, or microarray analysis. In some embodiments, one or more compounds are selected that (i) inhibit the expression or activity of mRNA molecules or proteins that promote cancer that are expressed at a higher than normal level or have a higher than normal level of activity in the subject (such as in a sample from the subject) or (ii) promote the expression or activity of mRNA molecules or proteins that inhibit cancer that are expressed at a lower than normal level or have a lower than normal level of activity in the subject. An individual or combination therapy that (i) modulates the greatest number of mRNA molecules or proteins that have mutations associated with cancer in the subject and (ii) modulates the least number of mRNA molecules or proteins that do not have mutations associated with cancer in the subject. In some embodiments, the selected individual or combination therapy has high drug efficacy and produces few, if any, adverse side-effects.

[00396] As an alternative to the subject-specific analysis described above, DNA chips can be used to compare the expression of mRNA molecules in a particular type of early or late-stage cancer (*e.g.*, breast cancer cells) to the expression in normal tissue (Marrack *et al.*, Current Opinion in Immunology 12, 206-209, 2000; Harkin, Oncologist. 5:501-507, 2000; Pelizzari *et al.*, Nucleic Acids Res. 28(22):4577-4581, 2000, which are each hereby incorporated by reference in its entirety). Based on this analysis, an individual or combination therapy for subjects with this type of cancer can be selected to modulate the expression of the mRNA or proteins that have altered expression in this type of cancer.

[00397] In addition to being used to select a therapy for a particular subject or group of subjects, expression profiling can be used to monitor the changes in mRNA and/or protein expression that occur during treatment. For example, expression profiling can be used to determine whether the

expression of cancer related genes has returned to normal levels. If not, the dose of one or more compounds in the therapy can be altered to either increase or decrease the effect of the therapy on the expression levels of the corresponding cancer related gene(s). In addition, this analysis can be used to determine whether a therapy affects the expression of other genes (*e.g.*, genes that are associated with adverse side-effects). If desired, the dose or composition of the therapy can be altered to prevent or reduce undesired side-effects.

Exemplary Formulations and Methods of Administration

[00398] For stabilizing, treating, or preventing a disease or disorder such as cancer or an increased risk for a disease or disorder such as cancer, a composition may be formulated and administered using any method known to those of skill in the art (see, *e.g.*, U.S. Pat. Nos. 8,389,578 and 8,389,557, which are each hereby incorporated by reference in its entirety). General techniques for formulation and administration are found in "Remington: The Science and Practice of Pharmacy," 21st Edition, Ed. David Troy, 2006, Lippincott Williams & Wilkins, Philadelphia, Pa., which is hereby incorporated by reference in its entirety). Liquids, slurries, tablets, capsules, pills, powders, granules, gels, ointments, suppositories, injections, inhalants, and aerosols are examples of such formulations. By way of example, modified or extended release oral formulation can be prepared using additional methods known in the art. For example, a suitable extended release form of an active ingredient may be a matrix tablet or capsule composition. Suitable matrix forming materials include, for example, waxes (*e.g.*, carnauba, bees wax, paraffin wax, ceresine, shellac wax, fatty acids, and fatty alcohols), oils, hardened oils or fats (*e.g.*, hardened rapeseed oil, castor oil, beef tallow, palm oil, and soya bean oil), and polymers (*e.g.*, hydroxypropyl cellulose, polyvinylpyrrolidone, hydroxypropyl methyl cellulose, and polyethylene glycol). Other suitable matrix tableting materials are microcrystalline cellulose, powdered cellulose, hydroxypropyl cellulose, ethyl cellulose, with other carriers, and fillers. Tablets may also contain granulates, coated powders, or pellets. Tablets may also be multi-layered. Optionally, the finished tablet may be coated or uncoated.

[00399] Typical routes of administering such compositions include, without limitation, oral, sublingual, buccal, topical, transdermal, inhalation, parenteral (*e.g.*, subcutaneous, intravenous, intramuscular, intrasternal injection, or infusion techniques), rectal, vaginal, and intranasal. In preferred embodiments, the therapy is administered using an extended release device.

Compositions of the invention are formulated so as to allow the active ingredient(s) contained therein to be bioavailable upon administration of the composition. Compositions may take the form of one or more dosage units. Compositions may contain 1, 2, 3, 4, or more active ingredients and may optionally contain 1, 2, 3, 4, or more inactive ingredients.

Alternate Embodiments

[00400] Any of the embodiments disclosed herein may be implemented in a computer system, digital electronic circuitry, integrated circuitry, specially designed ASICs (application-specific integrated circuits), computer hardware, firmware, software, non-transitory computer readable media, or in combinations thereof. Apparatus of the presently disclosed embodiments can be implemented in a computer program product tangibly embodied in a machine-readable storage device for execution by a programmable processor; and method steps of the presently disclosed embodiments can be performed by a programmable processor executing a program of instructions to perform functions of the presently disclosed embodiments by operating on input data and generating output. The presently disclosed embodiments can be implemented advantageously in one or more computer programs that are executable and/or interpretable on a programmable system including at least one programmable processor, which may be special or general purpose, coupled to receive data and instructions from, and to transmit data and instructions to, a storage system, at least one input device, and at least one output device. Each computer program can be implemented in a high-level procedural or object-oriented programming language or in assembly or machine language if desired; and in any case, the language can be a compiled or interpreted language. A computer program may be deployed in any form, including as a stand-alone program, or as a module, component, subroutine, or other unit suitable for use in a computing environment. A computer program may be deployed to be executed or interpreted on one computer or on multiple computers at one site, or distributed across multiple sites and interconnected by a communication network.

[00401] Computer readable storage media, as used herein, refers to physical or tangible storage (as opposed to signals) and includes without limitation volatile and non-volatile, removable and non-removable media implemented in any method or technology for the tangible storage of information such as computer-readable instructions, data structures, program modules or other data. Computer readable storage media includes, but is not limited to, non-transitory media,

RAM, ROM, EPROM, EEPROM, flash memory or other solid state memory technology, CD-ROM, DVD, or other optical storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other physical or material medium which can be used to tangibly store the desired information or data or instructions and which can be accessed by a computer or processor. The sequence data may be fed into a single computer or to another type of computing platform such as may be found in “the cloud.” The computing platform may calculate allele counts at the target loci from measurements made by the sequencer.

[00402] In some embodiments, the invention features a computer configured to accomplish one or more of the *in vitro* methods described herein, such as determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in the genome of one or more cells from an individual. In some embodiments, the computer system receives an input of genetic data, such as phased or unphased genetic data for the chromosome or chromosome segment of interest. The data is analyzed by the computer system as described herein.

[00403] Any of the methods described herein may include the output of data in a physical format, such as on a computer screen, or on a paper printout. Any of the methods of the invention may be combined with the output of the actionable data in a format that can be acted upon by a physician. Some of the embodiments described in the document for determining genetic data pertaining to a target individual may be combined with the notification of a potential chromosomal abnormality (such as a deletion or duplication), or lack thereof, with a medical professional, optionally combined with the decision to abort, or to not abort, a fetus in the context of prenatal diagnosis. Some of the embodiments described herein may be combined with the output of the actionable data, and the execution of a clinical decision that results in a clinical treatment, or the execution of a clinical decision to make no action.

[00404] In some embodiments, a method is disclosed herein for generating a report disclosing a result of any method of the invention (such as the presence or absence of a deletion or duplication). A report may be generated with a result from a method of the invention, and it may be sent to a physician electronically, displayed on an output device (such as a digital report), or a written report (such as a printed hard copy of the report) may be delivered to the physician. In addition, the described methods may be combined with the actual execution of a clinical decision that results in a clinical treatment, or the execution of a clinical decision to make no action.

[00405] Any of the embodiments described herein can be used in combination with any other embodiment described herein.

Experimental Section

[00406] The presently disclosed embodiments are described in the following Examples, which are set forth to aid in the understanding of the disclosure, and should not be construed to limit in any way the scope of the disclosure as defined in the claims which follow thereafter. The following examples are put forth so as to provide those of ordinary skill in the art with a complete disclosure and description of how to use the described embodiments, and is not intended to limit the scope of the disclosure nor is it intended to represent that the experiments below are all or the only experiments performed. Efforts have been made to ensure accuracy with respect to numbers used (*e.g.*, amounts, temperature, *etc.*) but some experimental errors and deviations should be accounted for. Unless indicated otherwise, parts are parts by volume, and temperature is in degrees Centigrade. It should be understood that variations in the methods as described may be made without changing the fundamental aspects that the experiments are meant to illustrate.

Example 1

[00407] Exemplary sample preparation and amplification methods are described in US Application No. 13/683,604, filed Nov. 21, 2012; U.S. Publication No. 2013/0123120, which is hereby incorporated by reference in its entirety. These methods can be used for analysis of any of the samples disclosed herein.

[00408] In one experiment, plasma samples were prepared and amplified using a hemi-nested 19,488-plex protocol. The samples were prepared in the following way: up to 20 mL of blood were centrifuged to isolate the buffy coat and the plasma. The genomic DNA in the blood sample was prepared from the buffy coat. Genomic DNA can also be prepared from a saliva sample. Cell-free DNA in the plasma was isolated using the QIAGEN CIRCULATING NUCLEIC ACID kit and eluted in 50 uL TE buffer according to manufacturer's instructions. Universal ligation adapters were appended to the end of each molecule of 40 uL of purified plasma DNA and libraries were amplified for 9 cycles using adaptor specific primers. Libraries were purified with AGENCOURT AMPURE beads and eluted in 50 ul DNA suspension buffer.

[00409] 6 ul of the DNA was amplified with 15 cycles of STAR 1 (95°C for 10 min for initial polymerase activation, then 15 cycles of 96°C for 30s; 65°C for 1 min; 58°C for 6 min; 60°C for 8 min; 65°C for 4 min and 72°C for 30s; and a final extension at 72°C for 2 min) using 7.5 nM primer concentration of 19,488 target-specific tagged reverse primers and one library adaptor specific forward primer at 500 nM.

[00410] The hemi-nested PCR protocol involved a second amplification of a dilution of the STAR 1 product for 15 cycles (STAR 2) (95°C for 10 min for initial polymerase activation, then 15 cycles of 95°C for 30s; 65°C for 1 min; 60°C for 5 min; 65°C for 5 min and 72°C for 30s; and a final extension at 72°C for 2 min) using reverse tag concentration of 1000 nM, and a concentration of 20 nM for each of 19,488 target-specific forward primers.

[00411] An aliquot of the STAR 2 products was then amplified by standard PCR for 12 cycles with 1 uM of tag-specific forward and barcoded reverse primers to generate barcoded sequencing libraries. An aliquot of each library was mixed with libraries of different barcodes and purified using a spin column.

[00412] In this way, 19,488 primers were used in the single-well reactions; the primers were designed to target SNPs found on chromosomes 1, 2, 13, 18, 21, X and Y. The amplicons were then sequenced using an ILLUMINA GAIIIX sequencer. If desired, the number of sequencing reads can be increased to increase the number of targeted SNPs that are amplified and sequenced.

[00413] Relevant genomic DNA samples amplified using a semi-nested 19,488 outer forward primers and tagged reverse primers at 7.5 nM in the STAR 1. Thermocycling conditions and composition of STAR 2, and the barcoding PCR were the same as for the hemi-nested protocol.

Example 2

[00414] Exemplary primer selection methods are described in US Application No. 13/683,604, filed Nov. 21, 2012 (U.S. Publication No. 2013/0123120, which is hereby incorporated by reference in its entirety). These methods can be used for analysis of any of the samples disclosed herein.

[00415] The following experiment illustrates an exemplary method for designing and selecting a library of primers that can be used in any of the multiplexed PCR methods of the

invention. The goal is to select primers from an initial library of candidate primers that can be used to simultaneously amplify a large number of target loci (or a subset of target loci) in a single reaction volume. For an initial set of candidate target loci, primers did not have to be designed or selected for each target locus. Preferably, primers are designed and selected for a large portion of the most desirable target loci.

Step 1

[00416] A set of candidate target loci (such as SNPs) were selected based on publically available information about desired parameters for the target loci, such as frequency of the SNPs within a target population or heterozygosity rate of the SNPs (worldwide web at ncbi.nlm.nih.gov/projects/SNP/; Sherry ST, Ward MH, Kholodov M, et al. dbSNP: the NCBI database of genetic variation. *Nucleic Acids Res.* 2001 Jan 1;29(1):308-11, which are each incorporated by reference in its entirety). For each candidate locus, one or more PCR primer pairs were designed using the Primer3 program (the worldwide web at primer3.sourceforge.net; libprimer3 release 2.2.3, which is hereby incorporated by reference in its entirety). If there were no feasible designs for PCR primers for a particular target locus, then that target locus was eliminated from further consideration.

[00417] If desired, a “target locus score” (higher score representing higher desirability) can be calculated for most or all of the target loci, such as a target locus score calculated based on a weighted average of various desired parameters for the target loci. The parameters may be assigned different weights based on their importance for the particular application that the primers will be used for. Exemplary parameters include the heterozygosity rate of the target locus, the disease prevalence associated with a sequence (*e.g.*, a polymorphism) at the target locus, the disease penetrance associated with a sequence (*e.g.*, a polymorphism) at the target locus, the specificity of the candidate primer(s) used to amplify the target locus, the size of the candidate primer(s) used to amplify the target locus, and the size of the target amplicon. In some embodiments, the specificity of the candidate primer for the target locus includes the likelihood that the candidate primer will mis-prime by binding and amplifying a locus other than the target locus it was designed to amplify. In some embodiments, one or more or all the candidate primers that mis-prime are removed from the library.

Step 2

[00418] A thermodynamic interaction score was calculated between each primer and all primers for all other target loci from Step 1 (*see, e.g.*, Allawi, H. T. & SantaLucia, J., Jr. (1998), "Thermodynamics of Internal C-T Mismatches in DNA", *Nucleic Acids Res.* 26, 2694-2701; Peyret, N., Seneviratne, P. A., Allawi, H. T. & SantaLucia, J., Jr. (1999), "Nearest-Neighbor Thermodynamics and NMR of DNA Sequences with Internal A-A, C-C, G-G, and T-T Mismatches", *Biochemistry* 38, 3468-3477; Allawi, H. T. & SantaLucia, J., Jr. (1998), "Nearest-Neighbor Thermodynamics of Internal A-C Mismatches in DNA: Sequence Dependence and pH Effects", *Biochemistry* 37, 9435-9444.; Allawi, H. T. & SantaLucia, J., Jr. (1998), "Nearest Neighbor Thermodynamic Parameters for Internal G-A Mismatches in DNA", *Biochemistry* 37, 2170-2179; and Allawi, H. T. & SantaLucia, J., Jr. (1997), "Thermodynamics and NMR of Internal G-T Mismatches in DNA", *Biochemistry* 36, 10581-10594; MultiPLX 2.1 (Kaplinski L, Andreson R, Puurand T, Remm M. MultiPLX: automatic grouping and evaluation of PCR primers. *Bioinformatics*. 2005 Apr 15;21(8):1701-2, which are each hereby incorporated by reference in its entirety). This step resulted in a 2D matrix of interaction scores. The interaction score predicted the likelihood of primer-dimers involving the two interacting primers. The score was calculated as follows:

$$\text{interaction\_score} = \max(-\text{deltaG\_2}, 0.8 * (-\text{deltaG\_1}))$$

where

deltaG_2 = Gibbs energy (energy required to break the dimer) for a dimer that is extensible by PCR on both ends, *i.e.*, the 3' end of each primer anneals to the other primer; and

deltaG_1 = Gibbs energy for a dimer that is extensible by PCR on at least one end.

Step 3:

[00419] For each target locus, if there was more than one primer-pair design, then one design was selected using the following method:

- 1 For each primer-pair design for the locus, find the worst-case (highest) interaction score for the two primers in that design and all primers from all designs for all other target loci.
- 2 Pick the design with the best (lowest) worst-case interaction score.

Step 4

[00420] A graph was built such that each node represented one locus and its associated primer-pair design (*e.g.*, a Maximal Clique problem). One edge was created between every pair of nodes. A weight was assigned to each edge equal to the worst-case (highest) interaction score between the primers associated with the two nodes connected by the edge.

Step 5

[00421] If desired, for every pair of designs for two different target loci where one of the primers from one design and one of the primers from the other design would anneal to overlapping target regions, an additional edge was added between the nodes for the two design. The weight of these edges was set equal to the highest weight assigned in Step 4. Thus, Step 5 prevents the library from having primers that would anneal to overlapping target regions, and thus interfere with each other during a multiplex PCR reaction.

Step 6

[00422] An initial interaction score threshold was calculated as follows:

$$\text{weight\_threshold} = \text{max}(\text{edge\_weight}) - 0.05 * (\text{max}(\text{edge\_weight}) - \text{min}(\text{edge\_weight}))$$

where

$\text{max}(\text{edge\_weight})$ is the maximum edge weight in the graph; and

$\text{min}(\text{edge\_weight})$ is the minimum edge weight in the graph.

The initial bounds for the threshold were set as follows:

`max_weight_threshold = max(edge_weight)`

`min_weight_threshold = min(edge_weight)`

Step 7

[00423] A new graph was constructed consisting of the same set of nodes as the graph from Step 5, only including edges with weights that exceed `weight_threshold`. Thus, step ignores interactions with scores equal to or below `weight_threshold`.

Step 8

[00424] Nodes (and all of the edges connected to the removed nodes) were removed from the graph of Step 7 until there were no edges left. Nodes were removed by applying the following procedure repeatedly:

- 1 Find the node with the highest degree (highest number of edges). If there is more than one then pick one arbitrarily.
- 2 Define the set of nodes consisting of the node picked above and all of the nodes connected to it, but excluding any nodes that have degree less than the node picked above.
- 3 Choose the node from the set that has the lowest target locus score (lower score representing lower desirability) from Step 1. Remove that node from the graph.

Step 9

[00425] If the number of nodes remaining in the graph satisfies the required number of target loci for the multiplexed PCR pool (within an acceptable tolerance), then the method was continued at Step 10.

[00426] If there were too many or too few nodes remaining in the graph, then a binary search was performed to determine what threshold values would result in the desired number of

nodes remaining in the graphs. If there were too many nodes in the graph then, the weight threshold bounds were adjusted as follows:

$$\text{max\_weight\_threshold} = \text{weight\_threshold}$$

Otherwise (if there are too few nodes in the graph), then the weight threshold bounds were adjusted as follows:

$$\text{min\_weight\_threshold} = \text{weight\_threshold}$$

Then, the weight threshold was adjusted follows:

$$\text{weight\_threshold} = (\text{max\_weight\_threshold} + \text{min\_weight\_threshold}) / 2$$

Steps 7-9 were repeated.

Step 10

[00427] The primer-pair designs associated with the nodes remaining in the graph were selected for the library of primers. This primer library can be used in any of the methods of the invention.

[00428] If desired, this method of designing and selecting primers can be performed for primer libraries in which only one primer (instead of a primer pair) is used for amplification of a target locus. In this case, a node presents one primer per target locus (rather than a primer pair).

Example 3

[00429] If desired, methods of the invention can be tested to evaluate their ability to detect a deletion or duplication of a chromosome or chromosome segment. The following experiment was performed to demonstrate the detection of an overrepresentation of the X chromosome or a segment from the X chromosome inherited from the father compared to the X chromosome or X chromosome segment from the mother. This assay is designed to mimic a deletion or duplication of a chromosome or chromosome segment. Different amounts of DNA from a father (with XY sex chromosomes) were mixed with DNA from a daughter (with XX sex chromosomes) of the father for analysis of the extra amount of X chromosome from the father (FIGS. 19A-19D).

[00430] DNA from father and daughter cells lines was extracted and quantified using Qubit. Father cell line AG16782, cAG16782-2-F and daughter cell line AG16777, cAG16777-2-P were used. To determine the father's haplotype for the X chromosome, SNPs were detected that are present on the X chromosome but not on the Y chromosome, so there would be a signal from the father's X chromosome but not Y chromosome. The daughter inherited this haplotype from the father. The haplotype from the other X chromosome in the daughter was inherited from her mother. This haplotype from the mother can be determined by assigning the SNPs in the DNA from the daughter cell line that were not inherited from the father to the haplotype from the mother.

[00431] To determine whether an overrepresentation of the X chromosome from the father could be detected, different amounts DNA from the father cell line were mixed with DNA from the daughter cell line. The total DNA input was approximately 75 ng (~25k copies) of genomic DNA. Approximately 3,456 SNPs were amplified using direct multiplex PCR for X and Y chromosome assays. The amplified products were sequenced using 50 bp single run sequencing with 7 bp barcodes using the Rapid/HT mode. The number of reads was approximately 10K per SNP.

[00432] As shown in FIGs. 19A-19D, mosaicism from the father's DNA could be detected. These figures indicate that chromosomes segments or entire chromosomes that are overrepresented can be detected.

[00433] All patents, patent applications, and published references cited herein are hereby incorporated by reference in their entirety. While the methods of the present disclosure have been described in connection with the specific embodiments thereof, it will be understood that it is capable of further modification. Furthermore, this application is intended to cover any variations, uses, or adaptations of the methods of the present disclosure, including such departures from the present disclosure as come within known or customary practice in the art to which the methods of the present disclosure pertain, and as fall within the scope of the appended claims. Any of the embodiments of the invention can be performed by analyzing the DNA and/or RNA in a sample. For example, any of the methods disclosed herein for DNA can be readily adapted for RNA, for example, by including a reverse transcription step to convert the RNA into DNA.

CLAIMS

What is claimed is:

1. A method for determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in the genome of one or more cells from an individual comprising:

obtaining phased genetic data for the first homologous chromosome segment comprising, for each locus in a set of polymorphic loci on the first homologous chromosome segment, the identity of the allele present at that locus on the first homologous chromosome segment,

obtaining phased genetic data for the second homologous chromosome segment comprising, for each locus in the set of polymorphic loci on the second homologous chromosome segment, the identity of the allele present at that locus on the second homologous chromosome segment,

obtaining measured genetic allelic data comprising, for each of the alleles at each of the loci in the set of polymorphic loci, the amount of each allele present in a sample of DNA from one or more target cells and one or more non-target cells from the individual;

enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment;

calculating, for each of the hypotheses, expected genetic data for the plurality of loci in the sample from the obtained phased genetic data for one or more possible ratios of DNA from the one or more target cells to the total DNA in the sample;

calculating, on a computer, for each possible ratio of DNA and for each hypothesis, the data fit between the obtained genetic data of the sample and the expected genetic data for the sample for that possible ratio of DNA and for that hypothesis;

ranking one or more of the hypotheses according to the data fit; and

selecting the hypothesis that is ranked the highest, thereby determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment in the genome of one or more cells from the individual.

2. A method for determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in the genome of one or more cells from an individual comprising:

obtaining phased genetic data for the first homologous chromosome segment comprising, for each locus in a set of polymorphic loci on the first homologous chromosome segment, the identity of the allele present at that locus on the first homologous chromosome segment,

obtaining phased genetic data for the second homologous chromosome segment comprising, for each locus in the set of polymorphic loci on the second homologous chromosome segment, the identity of the allele present at that locus on the second homologous chromosome segment,

obtaining measured genetic allelic data comprising, for each of the alleles at each of the loci in the set of polymorphic loci, the amount of each allele present in a sample of DNA from one or more target cells and one or more non-target cells from the individual;

enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment;

calculating, for each of the hypotheses, expected genetic data for the plurality of loci in the sample from the obtained phased genetic data for one or more possible ratios of DNA from the one or more target cells to the total DNA in the sample;

calculating, on a computer, for each locus in the plurality of loci, each possible ratio of DNA, and each hypothesis, the likelihood that the hypothesis is correct by comparing the obtained genetic data of the sample for that locus and the expected genetic data for that locus for that possible ratio of DNA and for that hypothesis;

determining the combined probability for each hypothesis by combining the probabilities of that hypothesis for each locus and each possible ratio; and

selecting the hypothesis with the greatest combined probability, thereby determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment.

3. A method for determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in the genome of one or more cells from an individual comprising:

obtaining phased genetic data for the first homologous chromosome segment comprising, for each locus in a set of polymorphic loci on the first homologous chromosome segment, the identity of the allele present at that locus on the first homologous chromosome segment,

obtaining phased genetic data for the second homologous chromosome segment comprising, for each locus in the set of polymorphic loci on the second homologous chromosome segment, the identity of the allele present at that locus on the second homologous chromosome segment,

obtaining measured genetic allelic data comprising, for each of the alleles at each of the loci in the set of polymorphic loci, the amount of each allele present in a sample of DNA from one or more cells from the individual;

calculating allele ratios for one or more loci in the set of polymorphic loci that are heterozygous in at least one cell; wherein the calculated allele ratio for a particular locus is the measured quantity of one of the alleles divided by the total measured quantity of all the alleles for the locus; and

determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment by comparing, for one or more of the calculated allele ratios, the calculated allele ratio for a locus to an allele ratio that is expected for that locus if the first and second homologous chromosome segments are present in equal proportions.

4. The method of claim 3, wherein a calculated allele ratio is indicative of an overrepresentation of the number of copies of the first homologous chromosome segment if either:

(i) the allele ratio for the measured quantity of the allele present at that locus on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus is greater than the expected allele ratio for that locus, or

(ii) the allele ratio for the measured quantity of the allele present at that locus on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than the expected allele ratio for that locus.

5. The method of claim 3, wherein a calculated allele ratio is indicative of no overrepresentation of the number of copies of the first homologous chromosome segment if either:

(i) the allele ratio for the measured quantity of the allele present at that locus on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than or equal to the expected allele ratio for that locus, or

(ii) the allele ratio for the measured quantity of the allele present at that locus on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is greater than or equal to the expected allele ratio for that locus.

6. A method for determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in cell-free DNA from an individual comprising:

obtaining phased genetic data for the first homologous chromosome segment comprising, for each locus in a set of polymorphic loci on the first homologous chromosome segment, the identity of the allele present at that locus on the first homologous chromosome segment,

obtaining phased genetic data for the second homologous chromosome segment comprising, for each locus in the set of polymorphic loci on the second homologous chromosome segment, the identity of the allele present at that locus on the second homologous chromosome segment,

obtaining measured genetic allelic data comprising, for each of the alleles at each of the loci in the set of polymorphic loci, the amount of each allele present in a mixed sample of cell-free DNA from the individual; wherein the mixed sample comprises cell-free DNA from two or more genetically different cells;

calculating allele ratios for one or more loci in the set of polymorphic loci that are heterozygous in at least one cell; wherein the calculated allele ratio for a particular locus is the measured quantity of one of the alleles divided by the total measured quantity of all the alleles for the locus; and

determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment by comparing, for one or more of the calculated allele ratios,

the calculated allele ratio for a locus to an allele ratio that is expected for that locus if the first and second homologous chromosome segments are present in equal proportions;

wherein a calculated allele ratio is indicative of an overrepresentation of the number of copies of the first homologous chromosome segment if either:

- (i) the allele ratio for the measured quantity of the allele present at that locus on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus is greater than the expected allele ratio for that locus, or
- (ii) the allele ratio for the measured quantity of the allele present at that locus on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than the expected allele ratio for that locus; or

wherein a calculated allele ratio is indicative of no overrepresentation of the number of copies of the first homologous chromosome segment if either:

- (i) the allele ratio for the measured quantity of the allele present at that locus on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than or equal to the expected allele ratio for that locus, or
- (ii) the allele ratio for the measured quantity of the allele present at that locus on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is greater than or equal to the expected allele ratio for that locus.

7. The method of any one of claims 3-6, wherein each calculated allele ratio is the allele ratio for the measured quantity of the allele present at that locus on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus, wherein (i) a calculated allele ratio is indicative of an overrepresentation of the number of copies of the first homologous chromosome segment if the calculated allele ratio is greater than the expected allele ratio for that locus, or (ii) a calculated allele ratio is indicative of no overrepresentation of the number of copies of the first homologous chromosome segment if the calculated ratio is less than or equal to the expected allele ratio for that locus.

8. The method of any one of claims 3-7, comprising
calculating allele ratios for a plurality of loci in the set of polymorphic loci that are heterozygous in at least one cell;

determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment by comparing the calculated allele ratios to the expected allele ratios.

9. The method of any one of claims 3-8, wherein comparing the calculated allele ratios to the expected allele ratios comprises:

(i) determining, for each calculated allele ratio, whether the calculated allele ratio is above or below the expected allele ratio for a particular locus irrespective of the magnitude of the difference;

(ii) determining, for each calculated allele ratio, the magnitude of the difference between the calculated allele ratio and the expected allele ratio for a particular locus irrespective of whether the calculated allele ratio is above or below the expected allele ratio;

(iii) determining, for each calculated allele ratio, whether the calculated allele ratio is above or below the expected allele ratio and the magnitude of the difference for a particular locus;

(iv) determining whether an average or weighted average value for the calculated allele ratios is above or below an average or weighted average value of the expected allele ratios irrespective of the magnitude of the difference;

(v) determining the magnitude of the difference between an average or weighted average value for the calculated allele ratios and an average or weighted average value for the expected allele ratios irrespective of whether the average value or weighted average value for the calculated allele ratio is above or below the average or weighted average value of the expected allele ratio;

(vi) determining whether an average or weighted average value for the calculated allele ratios is above or below an average or weighted average value for the expected allele ratios and the magnitude of the difference;

(vii) determining an average or weighted average value of the magnitude of the difference between the calculated allele ratios and the expected allele ratios; or

(viii) a combination of two or more of (i) to (vii).

10. The method of any one of claims 3-9, comprising determining that there is an overrepresentation of the number of copies of the first homologous chromosome segment if:

(i) the number of calculated allele ratios that are indicative of an overrepresentation of the number of copies of the first homologous chromosome segment is above a first threshold value,

(ii) the number of calculated allele ratios that are indicative of no overrepresentation of the number of copies of the first homologous chromosome segment is below a second threshold value;

(iii) the magnitude of the difference between the calculated allele ratios that are indicative of an overrepresentation of the number of copies of the first homologous chromosome segment and the corresponding expected allele ratios is above a third threshold value,

(iv) the magnitude of the difference between the calculated allele ratios that are indicative of no overrepresentation of the number of copies of the first homologous chromosome segment and the corresponding expected allele ratios is below a fourth threshold value,

(v) the average or weighted average value of the calculated allele ratios for the measured quantity of the allele present on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus is greater than the average or weighted average value of the expected allele ratios by at least a fifth threshold value,

(vi) the average or weighted average value of the calculated allele ratios for the measured quantity of the allele present on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than the average or weighted average value of the expected allele ratios by at least a sixth threshold value,

(vii) the data fit between the calculated allele ratios and allele ratios that are predicted for an overrepresentation of the number of copies of the first homologous chromosome segment is below a seventh threshold value;

(viii) the data fit between the calculated allele ratios and allele ratios that are predicted for no overrepresentation of the number of copies of the first homologous chromosome segment is above an eighth threshold value; or

(ix) a combination of two or more of (i) to (viii).

11. The method of any one of claims 3-10, comprising determining that there is not an overrepresentation of the number of copies of the first homologous chromosome segment if:

(i) the number of calculated allele ratios that are indicative of an overrepresentation of the number of copies of the first homologous chromosome segment is below the first threshold value,

(ii) the number of calculated allele ratios that are indicative of no overrepresentation of the number of copies of the first homologous chromosome segment is above the second threshold value,

(iii) the magnitude of the difference between the calculated allele ratios that are indicative of an overrepresentation of the number of copies of the first homologous chromosome segment and the corresponding expected allele ratios is below a third threshold value,

(iv) the magnitude of the difference between the calculated allele ratios that are indicative of no overrepresentation of the number of copies of the first homologous chromosome segment and the corresponding expected allele ratios is above a fourth threshold value,

(v) the average or weighted average value of the calculated allele ratios for the measured quantity of the allele present on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus minus the average or weighted average value of the expected allele ratios is less than a fifth threshold value,

(vi) the average or weighted average value of the expected allele ratios minus the average or weighted average value of the calculated allele ratios for the measured quantity of the allele present on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than a sixth threshold value,

(vii) the data fit between the calculated allele ratios and allele ratios that are predicted for an overrepresentation of the number of copies of the first homologous chromosome segment is above a seventh threshold value;

(viii) the data fit between the calculated allele ratios and allele ratios that are predicted for no overrepresentation of the number of copies of the first homologous chromosome segment is below an eight threshold value; or

(ix) a combination of two or more of (i) to (viii).

12. The method of any one of claims 3-11, wherein determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment further comprises:

enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment;

estimating, for each hypothesis, either (i) predicted allele ratios for the loci that are heterozygous in at least one cell given the degree of overrepresentation specified by that hypothesis or (ii) an expected distribution of a test statistic calculated using the predicted allele ratios,

calculating, for each hypothesis, the likelihood that the hypothesis is correct by comparing either (i) the calculated allele ratios to the predicted allele ratios, or (ii) a test statistic calculated using the calculated allele ratios to the expected distribution of the test statistic calculated using the predicted allele ratios; and

determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment by selecting the hypothesis with the greatest likelihood.

13. The method of any one of claims 1-12, wherein the phased genetic data comprises probabilistic data.

14. The method of any one of claims 3-13, wherein determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment further comprises:

enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment;

estimating, for each hypothesis, predicted allele ratios for the loci that are heterozygous in at least one cell given the phased genetic data for the first homologous chromosome segment, the phased genetic data for the second homologous chromosome segment, and the degree of overrepresentation specified by that hypothesis,

calculating, for each hypothesis, the likelihood that the hypothesis is correct by comparing the calculated allele ratios to the predicted allele ratios; and

determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment by selecting the hypothesis with the greatest likelihood.

15. The method of any one of claims 1-14, wherein the overrepresentation of the number of copies of the first homologous chromosome segment is due to a duplication of the first homologous chromosome segment or a deletion of the second homologous chromosome segment in the genome of one or more of the cells.

16. The method of claim 15, wherein the total measured quantity of all the alleles for one or more of the loci is compared to a reference amount to determine whether the overrepresentation of the number of copies of the first homologous chromosome segment is due to a duplication of the first homologous chromosome segment or a deletion of the second homologous chromosome segment in the genome of one or more of the cells.

17. The method of claim 15, wherein the magnitude of the difference between the calculated allele ratio and the expected allele ratio for one or more loci is used to determine whether the overrepresentation of the number of copies of the first homologous chromosome segment is due to a duplication of the first homologous chromosome segment or a deletion of the second homologous chromosome segment in the genome of one or more of the cells.

18. The method of any one of claims 3-17, wherein the sample comprises DNA from a mixture of one or more target cells and one or more non-target cells, and wherein the method further comprises:

- calculating the ratio of DNA from the one or more target cells to the total DNA in the sample;

- enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment;

- estimating, for each hypothesis, either (i) predicted allele ratios for the loci that are heterozygous in at least one cell given calculated ratio of DNA and the degree of overrepresentation specified by that hypothesis or (ii) an expected distribution of a test statistic calculated using the predicted allele ratios and the calculated ratio of DNA,

calculating, for each hypothesis, the likelihood that the hypothesis is correct by comparing either (i) the calculated allele ratios to the predicted allele ratios, or (ii) a test statistic calculated using the calculated allele ratios and the calculated ratio of DNA to the expected distribution of the test statistic calculated using the predicted allele ratios and the calculated ratio of DNA; and

determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment by selecting the hypothesis with the greatest likelihood.

19. The method of any one of claims 3-18, wherein the sample comprises DNA from a mixture of one or more target cells and one or more non-target cells, and wherein the method further comprises:

enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment;

estimating, for each hypothesis, either (i) predicted allele ratios for the loci that are heterozygous in at least one cell given the degree of overrepresentation specified by that hypothesis or (ii) for one or more possible ratios of DNA, an expected distribution of a test statistic calculated using the predicted allele ratios and the possible ratio of DNA from the one or more target cells to the total DNA in the sample;

calculating, for each possible ratio of DNA, a data fit by comparing either (i) the calculated allele ratios to the predicted allele ratios, or (ii) a test statistic calculated using the calculated allele ratios and the possible ratio of DNA to the expected distribution of the test statistic calculated using the predicted allele ratios and the possible ratio of DNA;

ranking one or more of the hypotheses according to the data fit; and

selecting the hypothesis that is ranked the highest, thereby determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment.

20. The method of any one of claims 3-19, wherein the sample comprises DNA from a mixture of one or more target cells and one or more non-target cells, and wherein the method further comprises:

creating a partition of possible ratios that range from a lower limit to an upper limit for the ratio of DNA from the one or more target cells to the total DNA in the sample;

enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment;

estimating, for each of the possible ratios of DNA in the partition and for each hypothesis, either (i) predicted allele ratios for the loci that are heterozygous in at least one cell given the possible ratio of DNA and the degree of overrepresentation specified by that hypothesis or (ii) an expected distribution of a test statistic calculated using the predicted allele ratios and the possible ratio of DNA;

calculating, for each of the possible ratios of DNA in the partition and for each hypothesis, the likelihood that the hypothesis is correct by comparing either (i) the calculated allele ratios to the predicted allele ratios, or (ii) a test statistic calculated using the calculated allele ratios and the possible ratio of DNA to the expected distribution of the test statistic calculated using the predicted allele ratios and the possible ratio of DNA; and

determining the combined probability for each hypothesis by combining the probabilities of that hypothesis for each of the possible ratios in the partition; and

selecting the hypothesis with the greatest combined probability, thereby determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment.

21. The method of any one of claims 1-20, comprising determining that the first homologous chromosome segments are present in equal proportions if there is not an overrepresentation of the number of copies of the first homologous chromosome segment, and there is not an overrepresentation of the second homologous chromosome segment.

22. The method of any one of claims 3-21, wherein the expected allele ratio is 0.5 for biallelic loci.

23. The method of any one of claims 1-22, comprising applying a technique selected from the group consisting of maximum likelihood estimation, maximum a-posteriori estimation, Bayesian estimation, dynamic estimation, and expectation-maximization estimation to the obtained genetic data and the expected genetic data.

24. The method of any one of claims 1-23, wherein the sample comprises DNA from (i) one or more target cells, (ii) one or more non-target cells, or (iii) a mixture of one or more target cells and one or more non-target cells.

25. The method of claim 24, wherein the one or more target cells are cancer cell(s), and the one or more non-target cells are non-cancerous cell(s); and wherein the method comprises determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment in the genome of one or more of the cancer cells.

26. The method of claim 24, wherein the one or more target cells are genetically identical cancer cell(s), and the one or more non-target cells are non-cancerous cell(s); and wherein the method comprises determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment in the genome of the cancer cell(s).

27. The method of claim 24, wherein the one or more target cells are genetically non-identical cancer cell(s), and the one or more non-target cells are non-cancerous cell(s); and wherein the method comprises determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment in the genome of one or more of the genetically non-identical cancer cells.

28. The method of claim 24, wherein the sample comprises cell-free DNA from a mixture of one or more cancer cells and one or more non-cancerous cells, and wherein the method comprises determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment in the genome of one or more of the cancer cells.

29. The method of any one of claims 1-28, wherein the measured genetic allelic data is obtained by (i) sequencing the DNA in the sample or (ii) amplifying DNA in the sample and then sequencing the amplified DNA.

30. The method of any one of claims 1-29, wherein the loci comprise single nucleotide polymorphisms (SNPs).

31. The method of claim of any one of claims 1-31, comprising determining whether one or more of the cells comprise a chromosomal condition selected from the group consisting of nullsomy, monosomy, disomy, trisomy, tetrasomy, deletion, duplication, mosaicism, and combinations thereof.

32. A report comprising a result from the method of any one of claims 1-31.

33. A method for determining a number of copies of a chromosome or chromosome segment in the genome of one or more cells from an individual, comprising:

- obtaining genetic data at a set of polymorphic loci on the chromosome or chromosome segment in a sample of DNA from one or more cells from the individual by measuring the quantity of each allele at each locus;

- calculating allele ratios for the loci that are heterozygous in at least one cell; wherein the allele ratio for a particular locus is the measured quantity of one of the alleles divided by the total measured quantity of all the alleles for the locus;

- calculating a test statistic based on the magnitude of the difference between the calculated allele ratio and the expected allele ratio for each of the loci;

- enumerating a set of one or more hypotheses specifying the number of copies of the chromosome or chromosome segment in the genome of one or more of the cells;

- selecting which hypothesis is most likely based on the test statistic, thereby determining the number of copies of the chromosome or chromosome segment in the genome of one or more of the cells.

34. A method for determining a number of copies of a chromosome or chromosome segment in the genome of one or more from an individual, comprising:

- obtaining genetic data at a set of polymorphic loci on the chromosome or chromosome segment in a mixed sample of cell-free DNA from the individual; wherein the mixed sample comprises cell-free DNA from two or more genetically different cells;

calculating allele ratios for the loci that are heterozygous in at least one cell; wherein the allele ratio for a particular locus is the measured quantity of one of the alleles divided by the total measured quantity of all the alleles for the locus;

calculating a test statistic based on the magnitude of the difference between the calculated allele ratio and the expected allele ratio for each of the loci;

enumerating a set of one or more hypotheses specifying the number of copies of the chromosome or chromosome segment in the genome of one or more of the cells;

selecting which hypothesis is most likely based on the test statistic, thereby determining the number of copies of the chromosome or chromosome segment in the genome of one or more of the cells.

35. The method of claim 33 or 34, comprising

selecting one of the hypotheses if the probability that the test statistic belongs to a distribution of the test statistic for that hypothesis is above an upper threshold;

rejecting the hypothesis if the probability that the test statistic belongs to the distribution of the test statistic for that hypothesis is below an lower threshold; or

neither selecting nor rejecting the hypothesis if the probability that the test statistic belongs to the distribution of the test statistic for that hypothesis is between the lower threshold and the upper threshold, or if the probability is not determined with sufficiently high confidence.

36. The method of any one of claims 33-35, wherein the test statistic is assumed to have a normal distribution.

37. The method of any one of claims 33-36, wherein the test statistic Δ is calculated using the following formula

$$\Delta = \frac{\sum_{All\ Loci} (\delta_i - \mu_i)}{\sqrt{\sum_{All\ Loci} \sigma_i^2}}$$

wherein δ_i is the magnitude of the difference between the calculated allele ratio and the expected allele ratio for the i th loci;

wherein μ_i is the mean value of δ_i ; and

wherein σ_i^2 is the standard deviation of δ_i .

38. The method of any one of claims 33-37, wherein the sample comprises DNA from (i) one or more target cells, (ii) one or more non-target cells, or (iii) a mixture of one or more target cells and one or more non-target cells.

39. The method of claim 38, wherein the sample comprises DNA from a mixture of one or more target cells and one or more non-target cells, and wherein the one or more target cells are cancer cell(s), and the one or more non-target cells are non-cancerous cell(s); and wherein the method comprises determining the number of copies of the chromosome or chromosome segment in the genome of one or more of the cancer cells.

40. The method of any one of claims 33-39, wherein the loci comprise SNPs.

41. The method of any one of claims 33-40, comprising determining whether one or more of the cells comprise a chromosomal condition selected from the group consisting of nullsomy, monosomy, disomy, trisomy, tetrasomy, deletion, duplication, mosaicism, and combinations thereof.

42. A report comprising a result from the method of any one of claims 33-41.

43. A method for determining a number of copies of a chromosome segment of interest in the genome of a fetus, comprising:

obtaining phased genetic data for at least one biological parent of the fetus, wherein the phased genetic data comprises the identity of the allele present for each locus in a set of polymorphic loci on a first homologous chromosome segment and a second homologous chromosome segment in a pair of homologous chromosome segments that comprises the chromosome segment of interest;

obtaining genetic data at the set of polymorphic loci on the chromosome segment of interest in a mixed sample of DNA comprising fetal DNA and maternal DNA from the mother of the fetus by measuring the quantity of each allele at each locus;

enumerating a set of one or more hypotheses specifying, for one or both parents, the number of copies of the first homologous chromosome segment or portion thereof from the parent in the genome of the fetus, the number of copies of the second homologous chromosome segment or portion thereof from the parent in the genome of the fetus, and the total number of copies of the chromosome segment of interest present in the genome of the fetus;

calculating, for each of the hypotheses, expected genetic data for the plurality of loci in the mixed sample from the obtained phased genetic data from the parent(s);

calculating, on a computer, the data fit between the obtained genetic data of the mixed sample and the expected genetic data for the mixed sample;

ranking one or more of the hypotheses according to the data fit; and

selecting the hypothesis that is ranked the highest, thereby determining the number of copies of the chromosome segment of interest in the genome of the fetus.

44. A method for determining a number of copies of a chromosome or chromosome segment of interest in the genome of a fetus, comprising:

obtaining phased genetic data for at least one biological parent of the fetus, wherein the phased genetic data comprises the identity of the allele present for each locus in a set of polymorphic loci on a first homologous chromosome segment and a second homologous chromosome segment in the parent,

obtaining genetic data at the set of polymorphic loci on the chromosome or chromosome segment in a mixed sample of DNA comprising fetal DNA and maternal DNA from the mother of the fetus by measuring the quantity of each allele at each locus;

enumerating a set of one or more hypotheses specifying the number of copies of the chromosome or chromosome segment of interest present in the genome of the fetus;

creating, on a computer, for each of the hypotheses, a probability distribution of the expected quantity of each allele at each of the plurality of loci in mixed sample from the (i) the obtained phased genetic data from the parent(s) and (ii) the probability of one or more crossovers that may have occurred during the formation of a gamete that contributed a copy of the chromosome or chromosome segment of interest to the fetus;

calculating, on a computer, a fit, for each of the hypotheses, between (1) the obtained genetic data of the mixed sample and (2) the probability distribution of the expected quantity of each allele at each of the plurality of loci in mixed sample for that hypothesis;

ranking one or more of the hypotheses according to the data fit; and

selecting the hypothesis that is ranked the highest, thereby determining the number of copies of the chromosome segment of interest in the genome of the fetus.

45. The method of claim 43 or 44, comprising:

obtaining phased genetic data for the mother of the fetus;

enumerating a set of one or more hypotheses specifying the number of copies of the first homologous chromosome segment or portion thereof from the mother in the genome of the fetus, the number of copies of the second homologous chromosome segment or portion thereof from the mother in the genome of the fetus, and the total number of copies of the chromosome segment of interest present in the genome of the fetus; and

calculating, for each of the hypotheses, expected genetic data for the plurality of loci in the mixed sample from the obtained phased genetic data from the mother.

46. The method of claim 45, wherein the expected genetic data for each of the hypotheses comprises the identity and an amount of one or more alleles at each locus in the plurality of loci from the maternal DNA and fetal DNA in the mixed sample; and wherein calculating expected genetic data comprises:

determining a fraction of fetal DNA and a fraction of maternal DNA in the mixed sample;

calculating, for each locus in the plurality of loci, the expected amount of one or more of the alleles for that locus in the maternal DNA in the mixed sample using the identity of the allele(s) present at that locus in the obtained phased genetic data of the mother and the fraction of maternal DNA in the mixed sample; and

calculating, for each locus in the plurality of loci for each hypothesis, the expected amount of one or more of the alleles for that locus in the fetal DNA inherited from the mother in the mixed sample using the identity of the allele present at that locus in the first or second homologous chromosome segment from the mother that is specified by the hypothesis to have

been inherited by the fetus, the number of copies of the first or second homologous chromosome segment from the mother that is specified by the hypothesis to have been inherited by the fetus, and the fraction of fetal DNA in the mixed sample.

47. The method of claim 45, wherein the expected genetic data for each of the hypotheses comprises the identity and an amount of one or more alleles at each locus in the plurality of loci from the maternal DNA and fetal DNA in the mixed sample; and wherein calculating expected genetic data comprises:

- determining a fraction of fetal DNA and a fraction of maternal DNA in the mixed sample;

- calculating, for each locus in the plurality of loci, the expected amount of one or more of the alleles for that locus in the maternal DNA in the mixed sample using the identity of the allele(s) present at that locus in the obtained phased genetic data of the mother and the fraction of maternal DNA in the mixed sample; and

- calculating, for each locus in the plurality of loci for each hypothesis, the expected amount of one or more of the alleles for that locus in the fetal DNA inherited from the mother in the mixed sample using the identity of the allele present at that locus in the first or second homologous chromosome segment from the mother that is specified by the hypothesis to have been inherited by the fetus, the number of copies of the first or second homologous chromosome segment from the mother that is specified by the hypothesis to have been inherited by the fetus, the identity of one or more possible alleles at that locus in the first or second homologous chromosome segment from the father that is specified by the hypothesis to have been inherited by the fetus, the number of copies of the first or second homologous chromosome segment from the father that is specified by the hypothesis to have been inherited by the fetus, and the fraction of fetal DNA in the mixed sample.

48. The method of claim 43 or 44, comprising:

- obtaining phased genetic data for both the mother and father of the fetus;

- enumerating a set of one or more hypotheses specifying the number of copies of the first homologous chromosome segment or portion thereof from the mother in the genome of the fetus, the number of copies of the second homologous chromosome segment or portion thereof from

the mother in the genome of the fetus, the number of copies of the first homologous chromosome segment or portion thereof from the father in the genome of the fetus, the number of copies of the second homologous chromosome segment or portion thereof from the father in the genome of the fetus, and the total number of copies of the chromosome segment of interest present in the genome of the fetus; and

calculating, for each of the hypotheses, expected genetic data for the plurality of loci in the mixed sample from the obtained phased genetic data from the mother and obtained phased genetic data from the father.

49. The method of claim 48, wherein the expected genetic data for each of the hypotheses comprises the identity and an amount of one or more alleles at each locus in the plurality of loci from the maternal DNA and fetal DNA in the mixed sample; and wherein calculating expected genetic data comprises:

determining a fraction of fetal DNA and a fraction of maternal DNA in the mixed sample;

calculating, for each locus in the plurality of loci, the expected amount of one or more of the alleles for that locus in the maternal DNA in the mixed sample using the identity of the allele(s) present at that locus in the obtained phased genetic data of the mother and the fraction of maternal DNA in the mixed sample; and

calculating, for each locus in the plurality of loci for each hypothesis, the expected amount of one or more of the alleles for that locus in the fetal DNA in the mixed sample using the identity of the allele present at that locus in the first or second homologous chromosome segment from the mother that is specified by the hypothesis to have been inherited by the fetus, the number of copies of the first or second homologous chromosome segment from the mother that is specified by the hypothesis to have been inherited by the fetus, the identity of the allele present at that locus in the first or second homologous chromosome segment from the father that is specified by the hypothesis to have been inherited by the fetus, the number of copies of the first or second homologous chromosome segment from the father that is specified by the hypothesis to have been inherited by the fetus, and the fraction of fetal DNA in the mixed sample.

50. The method of any one of claims 43-49, comprising:

calculating, for each of the hypotheses, a probability distribution of expected genetic data for the plurality of loci in the mixed sample from the obtained phased genetic data from the parent(s); and

increasing the probability in the probability distribution of an a particular allele being present at a first locus in the mixed sample if that particular allele is present in the first homologous segment in the parent and an allele at a nearby locus in the first homologous segment in the parent is observed in the obtained genetic data of the mixed sample; or

decreasing the probability in the probability distribution of an a particular allele being present at a first locus in the mixed sample if that particular allele is present in the first homologous segment in the parent and an allele at a nearby locus in the first homologous segment in the parent is not observed in the obtained genetic data of the mixed sample.

51. The method of any one of claims 43-40, comprising:

obtaining phased genetic data for both the mother and father of the fetus;

enumerating a set of one or more hypotheses specifying the number of copies of the first homologous chromosome segment or portion thereof from the mother in the genome of the fetus, the number of copies of the second homologous chromosome segment or portion thereof from the mother in the genome of the fetus, the number of copies of the first homologous chromosome segment or portion thereof from the father in the genome of the fetus, the number of copies of the second homologous chromosome segment or portion thereof from the father in the genome of the fetus, and the total number of copies of the chromosome segment of interest present in the genome of the fetus;

calculating, for each of the hypotheses, a probability distribution of expected genetic data for the plurality of loci in the mixed sample from the obtained phased genetic data from the mother and father; and

increasing the probability in the probability distribution of an a particular allele being present at a first locus in the mixed sample if that particular allele is present in the first homologous segment in the mother or father and an allele at a nearby locus in the first homologous segment in that parent is observed in the obtained genetic data of the mixed sample;
or

decreasing the probability in the probability distribution of an a particular allele being present at a first locus in the mixed sample if that particular allele is present in the first homologous segment in the mother or father and an allele at a nearby locus in the first homologous segment in that parent is not observed in the obtained genetic data of the mixed sample.

52. The method of any one of claims 43-51, wherein one or more crossovers occurs during the formation of a gamete that contributed a copy of the chromosome segment of interest to the fetus; and wherein the crossover produces a chromosome segment of interest in the genome of the fetus that comprises a portion of the first homologous segment and a portion of the second homologous segment from the parent.

53. The method of claim 52, wherein the set of hypothesis comprises one or more hypotheses specifying the number of copies of the chromosome segment of interest in the genome of the fetus that comprises a portion of the first homologous segment and a portion of the second homologous segment from the parent.

54. The method of any one of claims 43-53, wherein the expected genetic data of the mixed sample comprises the expected amount of one or more of the alleles at each locus in the plurality of loci in the mixed sample for each of the hypotheses.

55. A method for determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in the genome of a fetus, comprising:

obtaining phased genetic data for the first homologous chromosome segment in the genome of the fetus comprising, for each locus in a set of polymorphic loci on the first homologous chromosome segment, the identity of the allele present at that locus on the first homologous chromosome segment,

obtaining phased genetic data for the second homologous chromosome segment in the genome of the fetus comprising, for each locus in the set of polymorphic loci on the second

homologous chromosome segment, the identity of the allele present at that locus on the second homologous chromosome segment,

obtaining measured genetic allelic data comprising, for each of the alleles at each of the loci in the set of polymorphic loci, the amount of each allele present in a mixed sample of DNA comprising fetal DNA and maternal DNA from the mother of the fetus;

calculating allele ratios for one or more loci in the set of polymorphic loci that are heterozygous in the fetus and/or heterozygous in the mother; wherein the calculated allele ratio for a particular locus is the measured quantity of one of the alleles divided by the total measured quantity of all the alleles for the locus; and

determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment by comparing, for one or more of the calculated allele ratios, the calculated allele ratio for a locus to an allele ratio that is expected for that locus if the first and second homologous chromosome segments are present in equal proportions.

56. The method of claim 55, wherein a calculated allele ratio is indicative of an overrepresentation of the number of copies of the first homologous chromosome segment if either:

(i) the allele ratio for the measured quantity of the allele present at that locus on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus is greater than the expected allele ratio for that locus, or

(ii) the allele ratio for the measured quantity of the allele present at that locus on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than the expected allele ratio for that locus.

57. The method of claim 55, wherein a calculated allele ratio is indicative of no overrepresentation of the number of copies of the first homologous chromosome segment if either:

(i) the allele ratio for the measured quantity of the allele present at that locus on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than or equal to the expected allele ratio for that locus, or

(ii) the allele ratio for the measured quantity of the allele present at that locus on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is greater than or equal to the expected allele ratio for that locus.

58. A method for determining if there is an overrepresentation of the number of copies of a first homologous chromosome segment as compared to a second homologous chromosome segment in the genome of a fetus that is gestating in a pregnant mother,, comprising:

obtaining phased genetic data for the first homologous chromosome segment in the genome of the fetus comprising, for each locus in a set of polymorphic loci on the first homologous chromosome segment, the identity of the allele present at that locus on the first homologous chromosome segment,

obtaining phased genetic data for the second homologous chromosome segment in the genome of the fetus comprising, for each locus in the set of polymorphic loci on the second homologous chromosome segment, the identity of the allele present at that locus on the second homologous chromosome segment,

obtaining measured genetic allelic data comprising, for each of the alleles at each of the loci in the set of polymorphic loci, the amount of each allele present in a mixed sample of cell-free DNA originating from a blood sample from the mother, wherein the sample comprises fetal cell-free DNA and maternal cell-free DNA;

calculating allele ratios for one or more loci in the set of polymorphic loci that are heterozygous in the fetus and/or heterozygous in the mother; wherein the calculated allele ratio for a particular locus is the measured quantity of one of the alleles divided by the total measured quantity of all the alleles for the locus; and

determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment by comparing, for one or more of the calculated allele ratios, the calculated allele ratio for a locus to an allele ratio that is expected for that locus if the first and second homologous chromosome segments are present in equal proportions;

wherein a calculated allele ratio is indicative of an overrepresentation of the number of copies of the first homologous chromosome segment if either:

(iii) the allele ratio for the measured quantity of the allele present at that locus on the first homologous chromosome divided by the total measured quantity of

all the alleles for the locus is greater than the expected allele ratio for that locus, or

- (iv) the allele ratio for the measured quantity of the allele present at that locus on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than the expected allele ratio for that locus; or

wherein a calculated allele ratio is indicative of no overrepresentation of the number of copies of the first homologous chromosome segment if either:

- (iii) the allele ratio for the measured quantity of the allele present at that locus on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than or equal to the expected allele ratio for that locus, or
- (iv) the allele ratio for the measured quantity of the allele present at that locus on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is greater than or equal to the expected allele ratio for that locus.

59. The method of any one of claims 55-58, wherein each calculated allele ratio is the allele ratio for the measured quantity of the allele present at that locus on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus, wherein (i) a calculated allele ratio is indicative of an overrepresentation of the number of copies of the first homologous chromosome segment if the calculated allele ratio is greater than the expected allele ratio for that locus, or (ii) a calculated allele ratio is indicative of no overrepresentation of the number of copies of the first homologous chromosome segment if the calculated ratio is less than or equal to the expected allele ratio for that locus.

60. The method of any one of claims 55-59, comprising
calculating allele ratios for a plurality of loci in the set of polymorphic loci that are heterozygous in the fetus and/or heterozygous in the mother;

determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment by comparing the calculated allele ratios to the expected alleleratios.

61. The method of any one of claims 55-60, wherein comparing the calculated allele ratios to the expected allele ratios comprises:

- (i) determining, for each calculated allele ratio, whether the calculated allele ratio is above or below the expected allele ratio for a particular locus irrespective of the magnitude of the difference;
- (ii) determining, for each calculated allele ratio, the magnitude of the difference between the calculated allele ratio and the expected allele ratio for a particular locus irrespective of whether the calculated allele ratio is above or below the expected allele ratio;
- (iii) determining, for each calculated allele ratio, whether the calculated allele ratio is above or below the expected allele ratio and the magnitude of the difference for a particular locus;
- (iv) determining whether the average or weighted average value of the calculated allele ratios is above or below the average or weighted average value of the expected allele ratios irrespective of the magnitude of the difference;
- (v) determining the magnitude of the difference between the average or weighted average value of the calculated allele ratios and the average or weighted average value of the expected allele ratios irrespective of whether the average or weighted average value of the calculated allele ratio is above or below the average or weighted average value of the expected alleleratio;
- (vi) determining whether the average or weighted average value of the calculated allele ratios is above or below the average or weighted average value of the expected allele ratios and the magnitude of the difference; or
- (vii) determining an average or weighted average value of the magnitude of the difference between the calculated allele ratios and the expected allele ratios; or
- (viii) a combination of two or more of (i) to (vii).

62. The method of any one of claims 55-61, comprising determining that there is an overrepresentation of the number of copies of the first homologous chromosome segment if:

(i) the number of calculated allele ratios that are indicative of an overrepresentation of the number of copies of the first homologous chromosome segment is above a first threshold value,

(ii) the number of calculated allele ratios that are indicative of no overrepresentation of the number of copies of the first homologous chromosome segment is below a second threshold value;

(iii) the magnitude of the difference between the calculated allele ratios that are indicative of an overrepresentation of the number of copies of the first homologous chromosome segment and the corresponding expected allele ratios is above a third threshold value,

(iv) the magnitude of the difference between the calculated allele ratios that are indicative of no overrepresentation of the number of copies of the first homologous chromosome segment and the corresponding expected allele ratios is below a fourth threshold value,

(v) the average or weighted average value of the calculated allele ratios for the measured quantity of the allele present on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus is greater than the average or weighted average value of the expected allele ratios by at least a fifth threshold value,

(vi) the average or weighted average value of the calculated allele ratios for the measured quantity of the allele present on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than the average or weighted average value of the expected allele ratios by at least a sixth threshold value,

(vii) the data fit between the calculated allele ratios and allele ratios that are predicted for an overrepresentation of the number of copies of the first homologous chromosome segment is below a seventh threshold value;

(viii) the data fit between the calculated allele ratios and allele ratios that are predicted for no overrepresentation of the number of copies of the first homologous chromosome segment is above an eight threshold value; or

(ix) a combination of two or more of (i) to (viii).

63. The method of any one of claims 55-62, comprising determining that there is not an overrepresentation of the number of copies of the first homologous chromosome segment if:

(i) the number of calculated allele ratios that are indicative of an overrepresentation of the number of copies of the first homologous chromosome segment is below the first threshold value,

(ii) the number of calculated allele ratios that are indicative of no overrepresentation of the number of copies of the first homologous chromosome segment is above the second threshold value,

(iii) the magnitude of the difference between the calculated allele ratios that are indicative of an overrepresentation of the number of copies of the first homologous chromosome segment and the corresponding expected allele ratios is below a third threshold value,

(iv) the magnitude of the difference between the calculated allele ratios that are indicative of no overrepresentation of the number of copies of the first homologous chromosome segment and the corresponding expected allele ratios is above a fourth threshold value,

(v) the average or weighted average value of the calculated allele ratios for the measured quantity of the allele present on the first homologous chromosome divided by the total measured quantity of all the alleles for the locus minus the average or weighted average value of the expected allele ratios is less than a fifth threshold value,

(vi) the average or weighted average value of the expected allele ratios minus the average or weighted average value of the calculated allele ratios for the measured quantity of the allele present on the second homologous chromosome divided by the total measured quantity of all the alleles for the locus is less than a sixth threshold value,

(vii) the data fit between the calculated allele ratios and allele ratios that are predicted for an overrepresentation of the number of copies of the first homologous chromosome segment is above a seventh threshold value;

(viii) the data fit between the calculated allele ratios and allele ratios that are predicted for no overrepresentation of the number of copies of the first homologous chromosome segment is below an eight threshold value; or

(ix) a combination of two or more of (i) to (viii).

64. The method of any one of claims 55-63, wherein determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment further comprises:

- enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment;

- estimating, for each hypothesis, either (i) predicted allele ratios for the loci that are heterozygous in the fetus and/or heterozygous in the mother given the degree of overrepresentation specified by that hypothesis or (ii) an expected distribution of a test statistic calculated using the predicted allele ratios,

- calculating, for each hypothesis, the likelihood that the hypothesis is correct by comparing either (i) the calculated allele ratios to the predicted allele ratios, or (ii) a test statistic calculated using the calculated allele ratios to the expected distribution of the test statistic calculated using the predicted allele ratios; and

- determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment by selecting the hypothesis with the greatest likelihood.

65. The method of any one of claims 55-64, wherein determining if there is an overrepresentation of the number of copies of the first homologous chromosome segment further comprises:

- enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment;

- estimating, for each hypothesis, predicted allele ratios for the loci that are heterozygous in the fetus and/or heterozygous in the mother given the phased genetic data for the first homologous chromosome segment, the phased genetic data for the second homologous chromosome segment, and the degree of overrepresentation specified by that hypothesis,

- calculating, for each hypothesis, the likelihood that the hypothesis is correct by comparing the calculated allele ratios to the predicted allele ratios; and

- determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment by selecting the hypothesis with the greatest likelihood.

66. The method of any one of claims 43-61, wherein the overrepresentation of the number of copies of the first homologous chromosome segment is due to a duplication of the first homologous chromosome segment or a deletion of the second homologous chromosome segment in the genome of the fetus.

67. The method of claim 66, wherein the total measured quantity of all the alleles for one or more of the loci is compared to a reference amount to determine whether the overrepresentation of the number of copies of the first homologous chromosome segment is due to a duplication of the first homologous chromosome segment or a deletion of the second homologous chromosome segment in the genome of the fetus.

68. The method of claim 66, wherein the magnitude of the difference between the calculated allele ratio and the expected allele ratio for one or more loci is used to determine whether the overrepresentation of the number of copies of the first homologous chromosome segment is due to a duplication of the first homologous chromosome segment or a deletion of the second homologous chromosome segment in the genome of the fetus.

69. The method of any one of claims 55-68, wherein the method further comprises:
calculating the ratio of fetal DNA to the total DNA in the sample;
enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment;
estimating, for each hypothesis, either (i) predicted allele ratios for the loci that are heterozygous in the fetus and/or heterozygous in the mother given calculated ratio of DNA and the degree of overrepresentation specified by that hypothesis or (ii) an expected distribution of a test statistic calculated using the predicted allele ratios and the calculated ratio of DNA,
calculating, for each hypothesis, the likelihood that the hypothesis is correct by comparing either (i) the calculated allele ratios to the predicted allele ratios, or (ii) a test statistic calculated using the calculated allele ratios and the calculated ratio of DNA to the expected distribution of the test statistic calculated using the predicted allele ratios and the calculated ratio of DNA; and
determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment by selecting the hypothesis with the greatest likelihood.

70. The method of any one of claims 43-69, wherein the ratio of fetal DNA to total DNA in the sample is determined by measuring the amount of an allele at one or more loci in which the fetus has the allele and the mother does not have the allele.

71. The method of any one of claims 43-70, wherein the ratio of fetal DNA to total DNA in the sample is determined by measuring the difference in methylation between one or more maternal and fetal alleles.

72. The method of any one of claims 55-71, wherein the method further comprises:
enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment;

estimating, for each hypothesis, either (i) predicted allele ratios for the loci that are heterozygous in the fetus and/or heterozygous in the mother given the degree of overrepresentation specified by that hypothesis or (ii) for one or more possible ratios of DNA, an expected distributions of a test statistic calculated using the predicted allele ratios and the possible ratio of fetal DNA to the total DNA in the sample;

calculating, for each possible ratio of DNA, a data fit by comparing either (i) the calculated allele ratios to the predicted allele ratios, or (ii) a test statistic calculated using the calculated allele ratios and the possible ratio of DNA to the expected distribution of the test statistic calculated using the predicted allele ratios and the possible ratio of DNA;

ranking one or more of the hypotheses according to the data fit; and
selecting the hypothesis that is ranked the highest, thereby determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment.

73. The method of any one of claims 55-72, wherein the method further comprises:
creating a partition of possible ratios that range from a lower limit to an upper limit for the ratio of fetal DNA to the total DNA in the sample;

enumerating a set of one or more hypotheses specifying the degree of overrepresentation of the first homologous chromosome segment;

estimating, for each of the possible ratios of DNA in the partition and for each hypothesis, either (i) predicted allele ratios for the loci that are heterozygous in the fetus and/or heterozygous in the mother given the possible ratio of DNA and the degree of overrepresentation specified by that hypothesis or (ii) an expected distribution of a test statistic calculated using the predicted allele ratios and the possible ratio of DNA;

calculating, for each of the possible ratios of DNA in the partition and for each hypothesis, the likelihood that the hypothesis is correct by comparing either (i) the calculated allele ratios to the predicted allele ratios, or (ii) a test statistic calculated using the calculated allele ratios and the possible ratio of DNA to the expected distribution of the test statistic calculated using the predicted allele ratios and the possible ratio of DNA; and

determining the combined probability for each hypothesis by combining the probabilities of that hypothesis for each of the possible ratios in the partition; and

selecting the hypothesis with the greatest combined probability, thereby determining the degree of overrepresentation of the number of copies of the first homologous chromosome segment.

74. The method of claim of any one of claims 43-73, comprising determining that the first homologous chromosome segments are present in equal proportions if there is not an overrepresentation of the number of copies of the first homologous chromosome segment, and there is not an overrepresentation of the second homologous chromosome segment.

75. The method of any one of claims 55-74, wherein the expected allele ratio is 0.5 for biallelic loci.

76. The method of any one of claims 43-75, wherein the phased genetic data comprises probabilistic data.

77. The method of any one of claims 55-76, wherein obtaining the phased genetic data for the first homologous chromosome segment and/or the second homologous chromosome segment in the genome of the fetus comprises:

obtaining phased genetic data for the first homologous chromosome segment and/or the second homologous chromosome segment in the genome of one or both biological parents of the fetus, and

inferring which homologous chromosome segment the fetus inherited from one or both biological parents.

78. The method of any one of claims 43-77, comprising using the probability of one or more crossovers that may have occurred during the formation of a gamete that contributed a copy of the first homologous chromosome segment or the second homologous chromosome segment to the fetus individual to infer which homologous chromosome segment(s) the fetus inherited from one or both biological parents.

79. The method of any one of claims 43-78, wherein phased genetic data for the mother or father of the fetus is obtained using digital PCR or population based haplotype frequencies.

80. The method of any one of claims 43-79, comprising applying a technique selected from the group consisting of maximum likelihood estimation, maximum a-posteriori estimation, Bayesian estimation, dynamic estimation, and expectation-maximization estimation to the obtained genetic data of the mixed sample and the expected genetic data for the mixed sample.

81. The method of any one of claims 43-80, wherein the sample is obtained from a maternal whole blood sample or fraction thereof, cells isolated from a maternal blood sample, an amniocentesis sample, a products of conception sample, a placental tissue sample, a chorionic villus sample, a placental membrane sample, a cervical mucus sample, or a sample from a fetus.

82. The method of any one of claims 81, wherein the sample comprises cell-free DNA obtained from a blood sample or fraction thereof from the mother.

83. The method of claim of any one of claims 43-81, wherein the sample comprises nuclear DNA obtained from a mixture of fetal cells and maternal cells.

84. The method of claim 81, wherein the sample is obtained from a fraction of maternal blood containing nucleated cells that has been enriched for fetal cells.

85. The method of any one of claims 43-84, wherein the measured genetic allelic data is obtained by (i) sequencing the DNA in the sample or (ii) amplifying DNA in the sample and then sequencing the amplified DNA.

86. The method of any one of claims 43-85, wherein the loci comprise single nucleotide polymorphisms (SNPs).

87. The method of any one of claims 43-86, wherein the chromosome segment of interest is an entire chromosome.

88. The method of any one of claims 43-87, comprising determining whether the fetus has a chromosomal condition selected from the group consisting of nullsomy, monosomy, disomy, uniparental disomy, trisomy, matched trisomy, unmatched trisomy, maternal trisomy, paternal trisomy, triploidy, tetrasomy, matched tetrasomy, unmatched tetrasomy, unbalanced translocation, balanced translocation, recombination, deletion, duplication, insertion, recombination, mosaicism, and combinations thereof.

89. The method of any one of claims 43-88, comprising determining whether the fetus has a chromosomal condition selected from the group consisting of DiGeorge syndrome, DiGeorge 2 syndrome, DiGeorge/VCFS syndrome, Prader-Willi syndrome, Angelman syndrome, Beckwith-Wiedemann syndrome, 1p36 deletion syndrome, 2q37 deletion syndrome, 3q29 deletion syndrome, 9q34 deletion syndrome, 17q21.31 deletion syndrome, Cri-du-chat syndrome, Jacobsen syndrome, Miller Dieker syndrome, Phelan-McDermid syndrome, Smith-Magenis syndrome, WAGR syndrome, Wolf-Hirschhorn syndrome, Williams syndrome, Williams-Beuren syndrome, Miller-Dieker syndrome, Phelan-McDermid syndrome, Smith-Magenis syndrome, Down syndrome, Edward syndrome, Patau syndrome, Klinefelter syndrome, Turner syndrome, 47,XXX syndrome, 47,XYY syndrome, Sotos syndrome, and combinations thereof.

90. A report comprising a result from the method of any one of claims 43-89.

91. A method for determining a number of copies of a chromosome or chromosome segment in the genome of a fetus, comprising:

obtaining genetic data at a set of polymorphic loci on the chromosome or chromosome segment in a mixed sample of DNA comprising fetal DNA and maternal DNA from the mother of the fetus by measuring the quantity of each allele at each locus;

calculating allele ratios for the loci that are heterozygous in the fetus and/or heterozygous in the mother; wherein the allele ratio for a particular locus is the measured quantity of one of the alleles divided by the total measured quantity of all the alleles for the locus;

calculating a test statistic based on the magnitude of the difference between the calculated allele ratio and the expected allele ratio for each of the loci;

enumerating a set of one or more hypotheses specifying the number of copies of the chromosome or chromosome segment in the genome of the fetus;

selecting which hypothesis is most likely based on the test statistic, thereby determining the number of copies of the chromosome or chromosome segment in the genome of the fetus.

92. A method for determining a number of copies of a chromosome or chromosome segment in the genome of a fetus that is gestating in a pregnant mother, comprising:

obtaining genetic data at a set of polymorphic loci on the chromosome or chromosome segment in a mixed sample of cell-free DNA originating from a blood sample from the mother by measuring the quantity of each allele at each locus; wherein the sample comprises fetal cell-free DNA and maternal cell-free DNA;

calculating allele ratios for the loci that are heterozygous in the fetus and/or heterozygous in the mother; wherein the allele ratio for a particular locus is the measured quantity of one of the alleles divided by the total measured quantity of all the alleles for the locus;

calculating a test statistic based on the magnitude of the difference between the calculated allele ratio and the expected allele ratio for each of the loci;

enumerating a set of one or more hypotheses specifying the number of copies of the chromosome or chromosome segment in the genome of the fetus;

selecting which hypothesis is most likely based on the test statistic, thereby determining the number of copies of the chromosome or chromosome segment in the genome of the fetus.

93. The method of claim 91 or 92, comprising

selecting one of the hypotheses if the probability that the test statistic belongs to a distribution of the test statistic for that hypothesis is above an upper threshold;

rejecting the hypothesis if the probability that the test statistic belongs to the distribution of the test statistic for that hypothesis is below an lower threshold; or

neither selecting nor rejecting the hypothesis if the probability that the test statistic belongs to the distribution of the test statistic for that hypothesis is between the lower threshold and the upper threshold, or if the probability is not determined with sufficiently high confidence.

94. The method of any one of claims 91-93, wherein the test statistic is assumed to have a normal distribution.

95. The method of any one of claims 91-94, wherein the test statistic Δ is calculated using the following formula

$$\Delta = \frac{\sum_{All\ Loci} (\delta_i - \mu_i)}{\sqrt{\sum_{All\ Loci} \sigma_i^2}}$$

wherein δ_i is the magnitude of the difference between the calculated allele ratio and the expected allele ratio for the i th loci;

wherein μ_i is the mean value of δ_i ; and

wherein σ_i^2 is the standard deviation of δ_i .

96. The method of any one of claims 91-95, wherein the sample is obtained from a maternal whole blood sample or fraction thereof, cells isolated from a maternal blood sample, an amniocentesis sample, a products of conception sample, a placental tissue sample, a

chorionic villus sample, a placental membrane sample, a cervical mucus sample, or a sample from a fetus.

97. The method of claim 96, wherein the sample comprises cell-free DNA obtained from a blood sample or fraction thereof from the mother.

98. The method of any one of claims 91-96, wherein the sample comprises nuclear DNA obtained from a mixture of fetal cells and maternal cells.

99. The method of claim 96, wherein the sample is obtained from a fraction of maternal blood containing nucleated cells that has been enriched for fetal cells.

100. The method of any one of claims 91-99, wherein the measured genetic allelic data is obtained by (i) sequencing the DNA in the sample or (ii) amplifying DNA in the sample and then sequencing the amplified DNA.

101. The method of any one of claims 91-100, wherein the loci comprise single nucleotide polymorphisms (SNPs).

102. The method of any one of claims 91-101, comprising determining whether the fetus has a chromosomal condition selected from the group consisting of nullsomy, monosomy, disomy, uniparental disomy, trisomy, matched trisomy, unmatched trisomy, maternal trisomy, paternal trisomy, triploidy, tetrasomy, matched tetrasomy, unmatched tetrasomy, unbalanced translocation, balanced translocation, recombination, deletion, duplication, insertion, recombination, mosaicism, and combinations thereof.

103. The method of any one of claims 91-102, comprising determining whether the fetus has a chromosomal condition selected from the group consisting of DiGeorge syndrome, DiGeorge 2 syndrome, DiGeorge/VCFS syndrome, Prader-Willi syndrome, Angelman syndrome, Beckwith-Wiedemann syndrome, 1p36 deletion syndrome, 2q37 deletion syndrome, 3q29 deletion syndrome, 9q34 deletion syndrome, 17q21.31 deletion syndrome, Cri-du-chat

syndrome, Jacobsen syndrome, Miller Dieker syndrome, Phelan-McDermid syndrome, Smith-Magenis syndrome, WAGR syndrome, Wolf-Hirschhorn syndrome, Williams syndrome, Williams-Beuren syndrome, Miller-Dieker syndrome, Phelan-McDermid syndrome, Smith-Magenis syndrome, Down syndrome, Edward syndrome, Patau syndrome, Klinefelter syndrome, Turner syndrome, 47,XXX syndrome, 47,XYY syndrome, Sotos syndrome, and combinations thereof.

104. A report comprising a result from the method of any one of claims 91-103

105. The method of any one of claims 1-31, 33-41, 43-89, and 91-103, wherein the measured genetic allelic data or the genetic data is obtained by amplifying DNA in the sample using a polymerase with low 5'→3' exonuclease and/or low strand displacement activity.

106. A method for detecting a cancer phenotype in an individual, wherein the cancer phenotype is defined by the presence of at least one of a set of mutations, the method comprising:

obtaining DNA measurements for a sample of DNA from one or more cells from the individual, wherein one or more of the cells is suspected of having the cancer phenotype;

analyzing the DNA measurements to determine, for each of the mutations in the set of mutations, the likelihood that at least one of the cells has that mutation; and

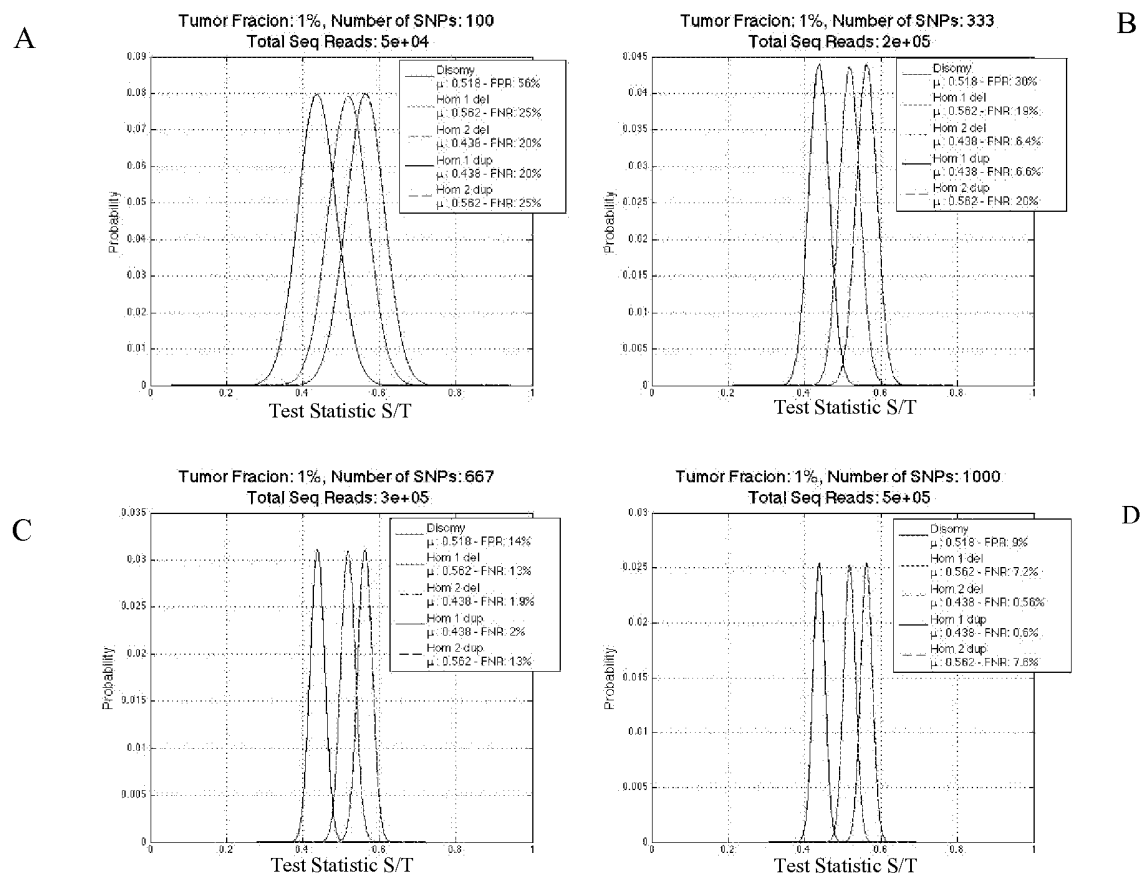
determining that the individual has the cancer phenotype if either (i) for at least one of the mutations, the likelihood that at least one of the cells contains that mutations is greater than a threshold, or (ii) for at least one of the mutations, the likelihood that at least one of the cells has that mutations is less than the threshold, and for a plurality of the mutations, the combined likelihood that at least one of the cells has at least one of the mutations is greater than the threshold.

ABSTRACT

[001] The invention provides methods of detecting deletions and duplications of chromosome segments or entire chromosomes. In some aspects, the invention features methods for diagnosing, prognosticating, preventing, delaying, stabilizing, or treating a disease or disorder in a mammal, such as cancer or a chromosomal abnormality in a gestating fetus.

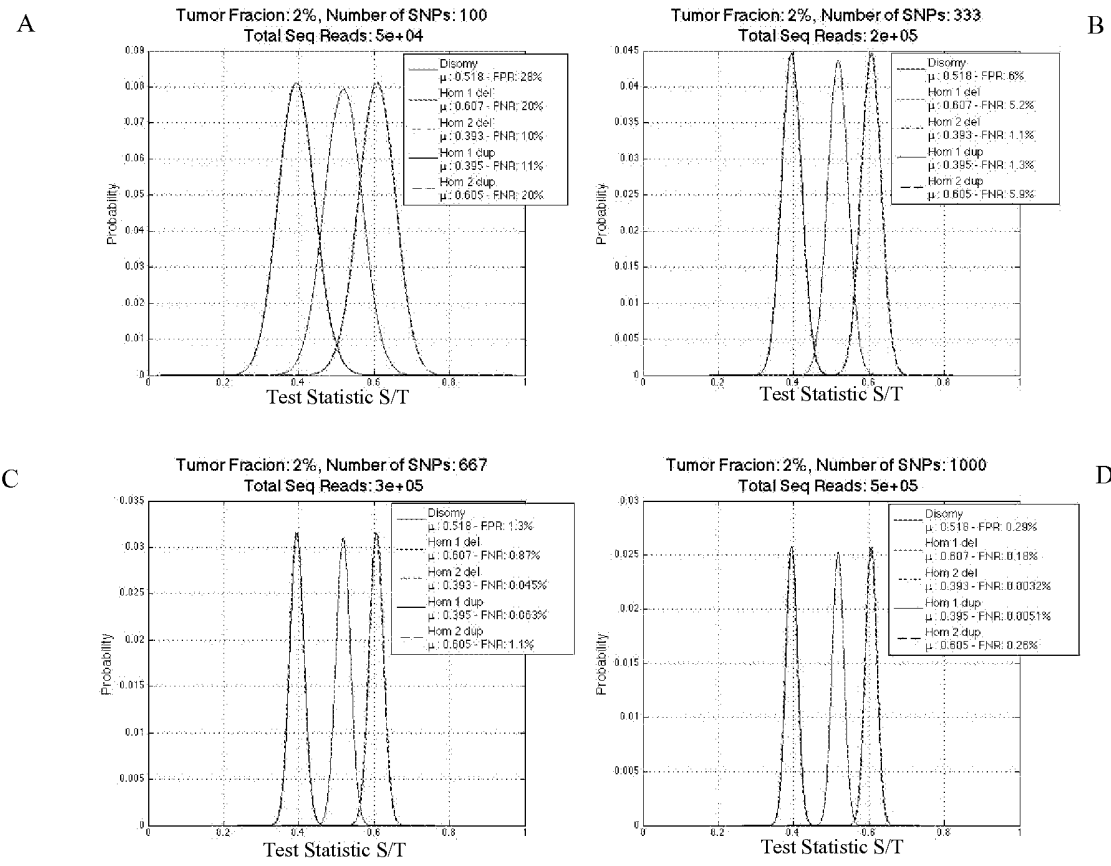
Figures 1A-1D

DOR of 500 and Tumor Fraction of 1%:



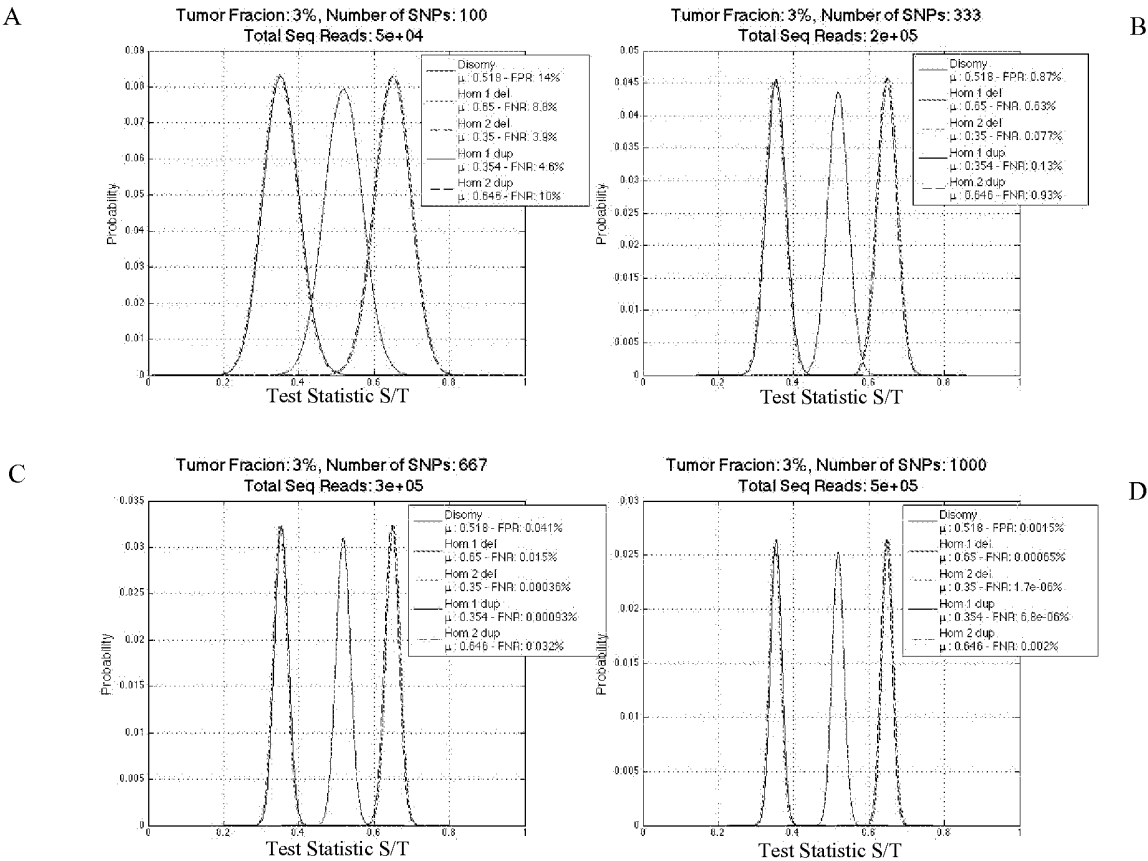
Figures 2A-2D

DOR of 500 and Tumor Fraction of 2%:



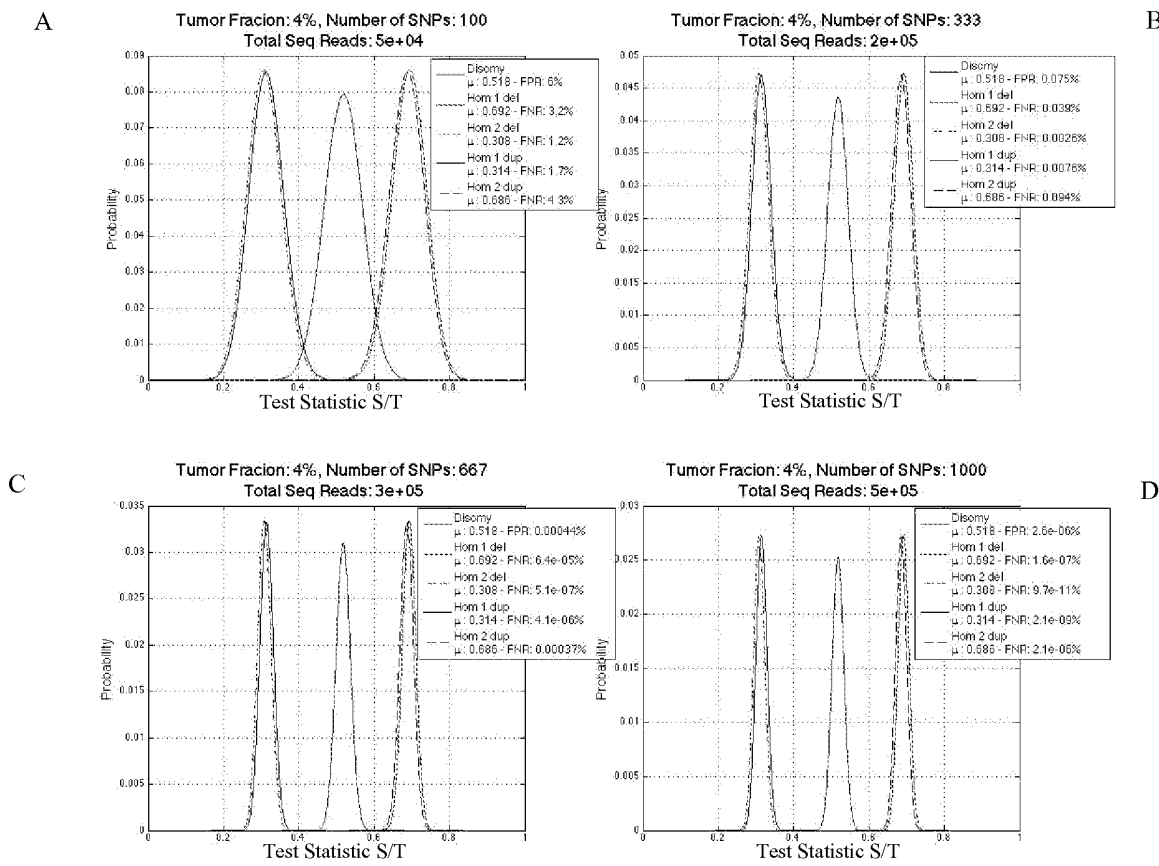
Figures 3A-3D

DOR of 500 and Tumor Fraction of 3%:



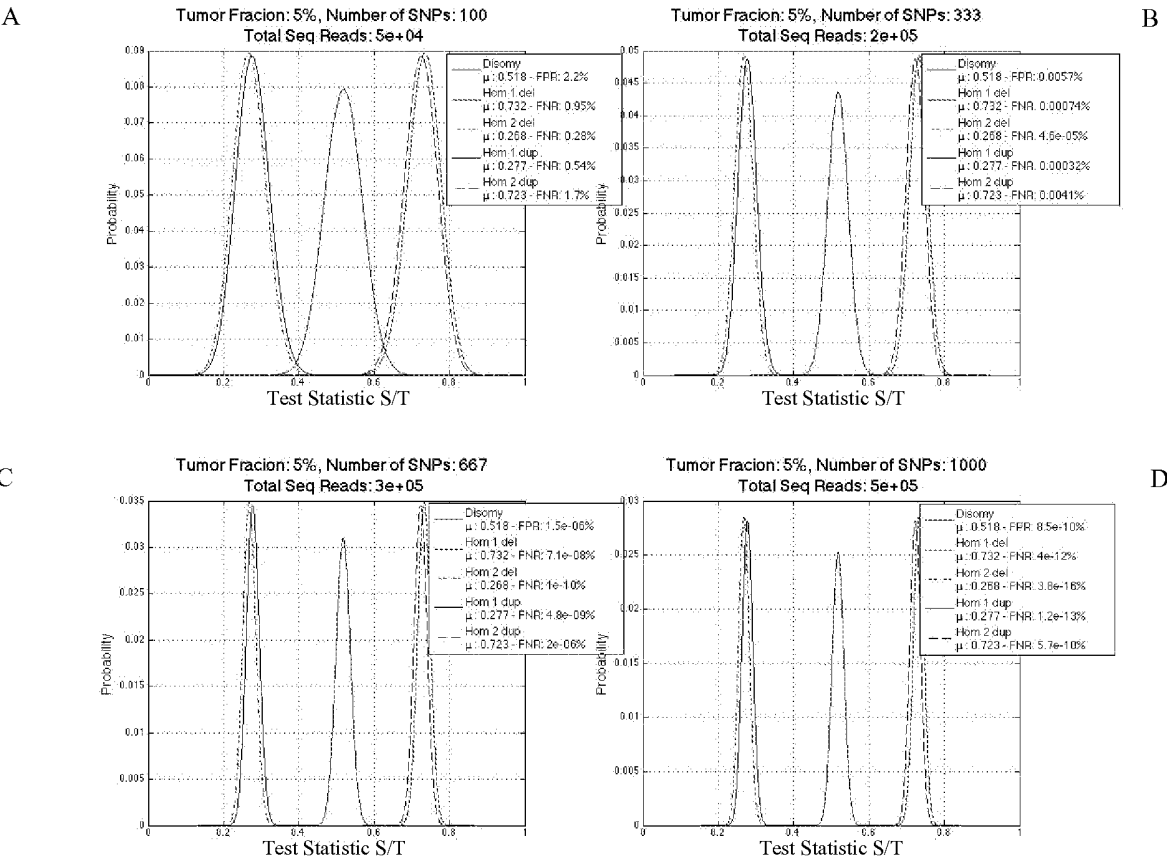
Figures 4A-4D

DOR of 500 and Tumor Fraction of 4%:



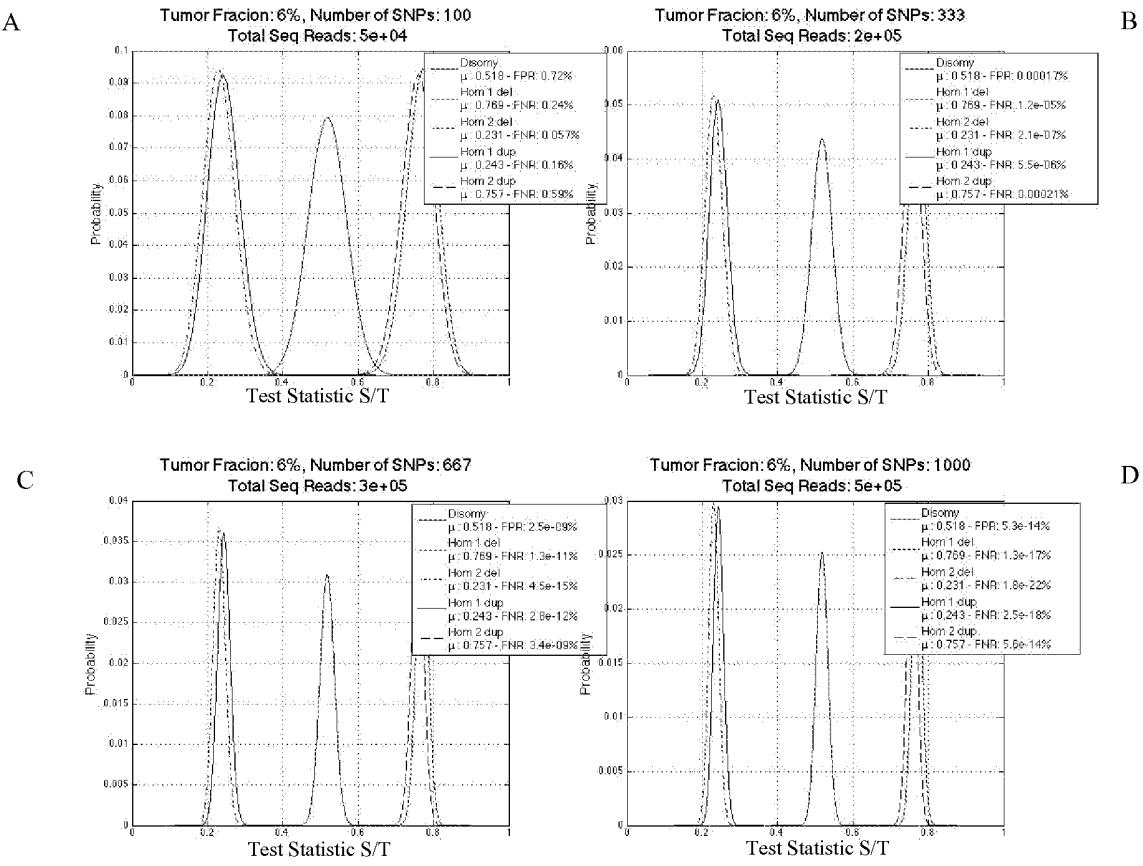
Figures 5A-5D

DOR of 500 and Tumor Fraction of 5%:



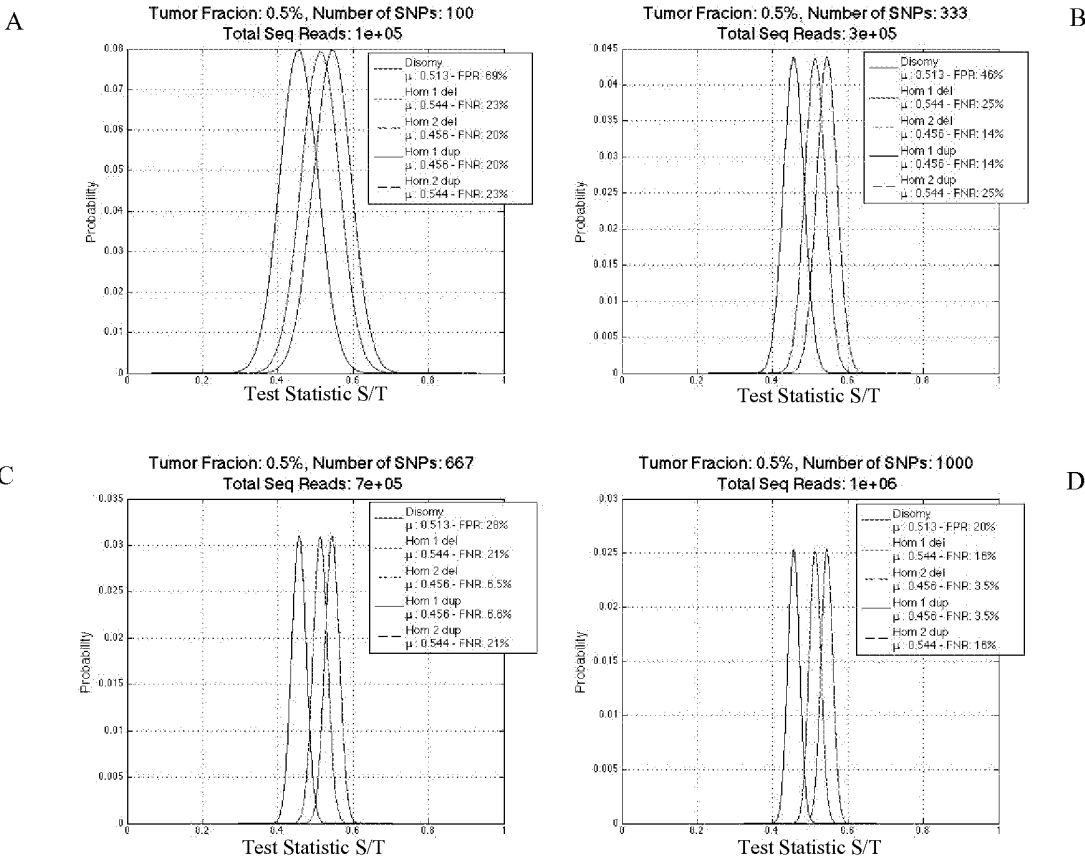
Figures 6A-6D

DOR of 500 and Tumor Fraction of 6%:



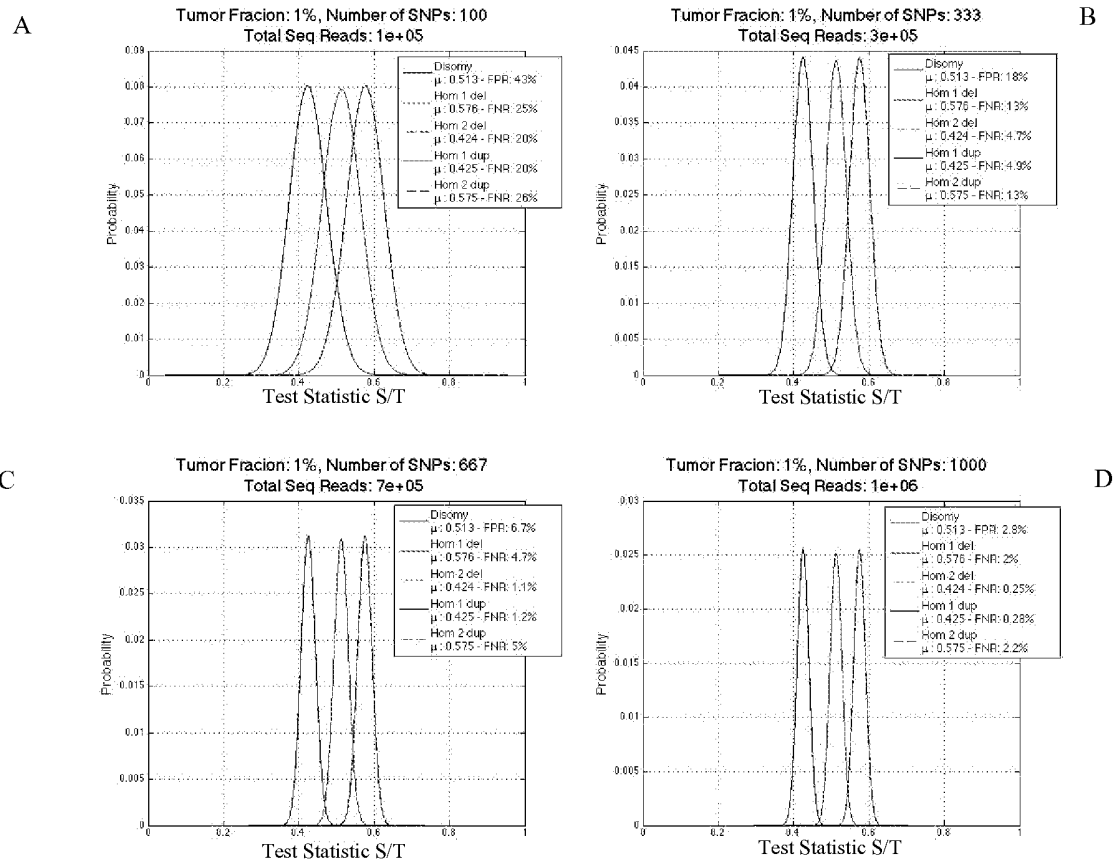
Figures 7A-7D

DOR of 1000 and Tumor Fraction of 0.5%:



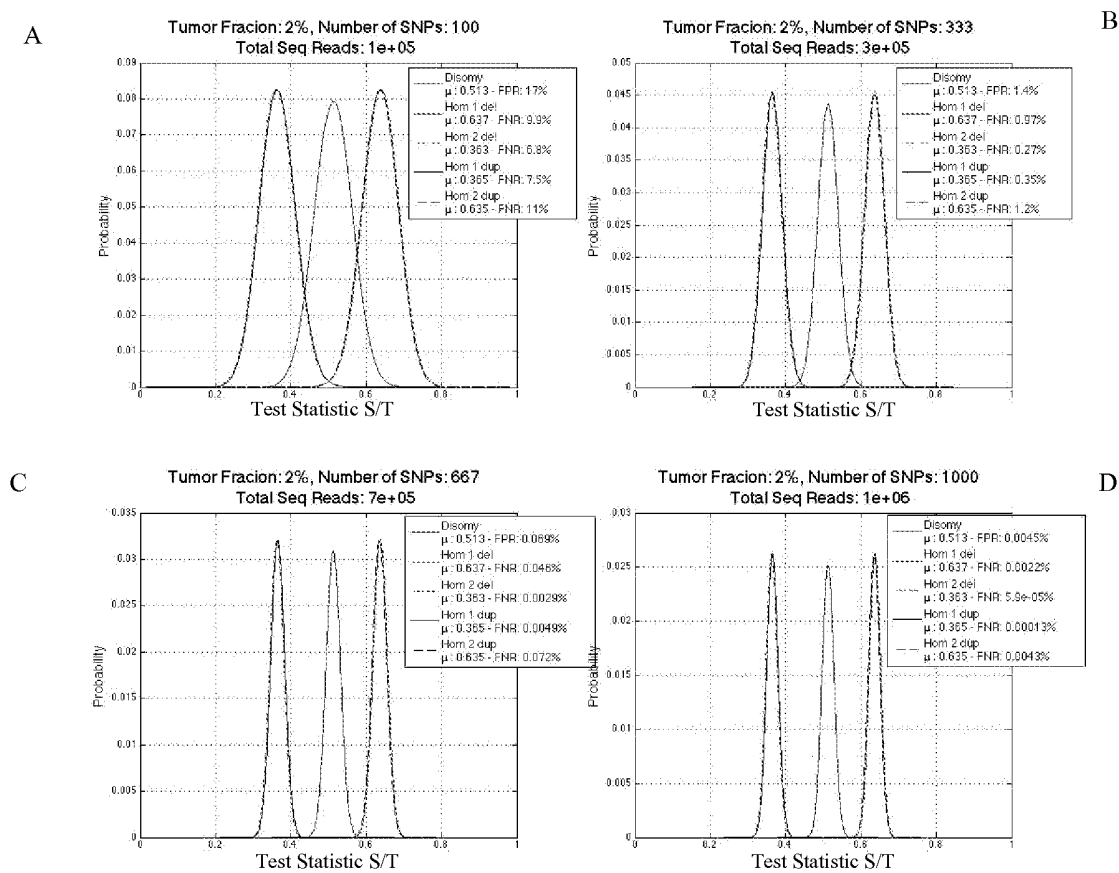
Figures 8A-8D

DOR of 1000 and Tumor Fraction of 1%:



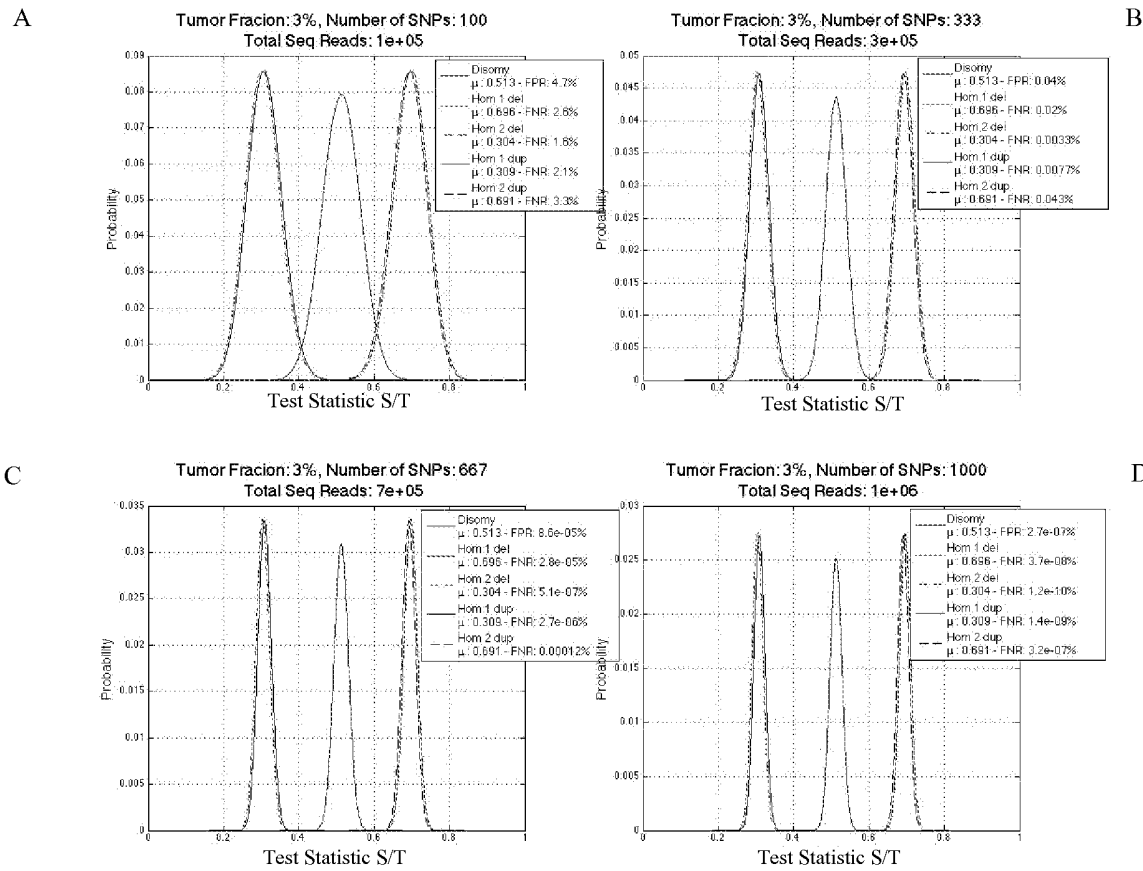
Figures 9A-9D

DOR of 1000 and Tumor Fraction of 2%:



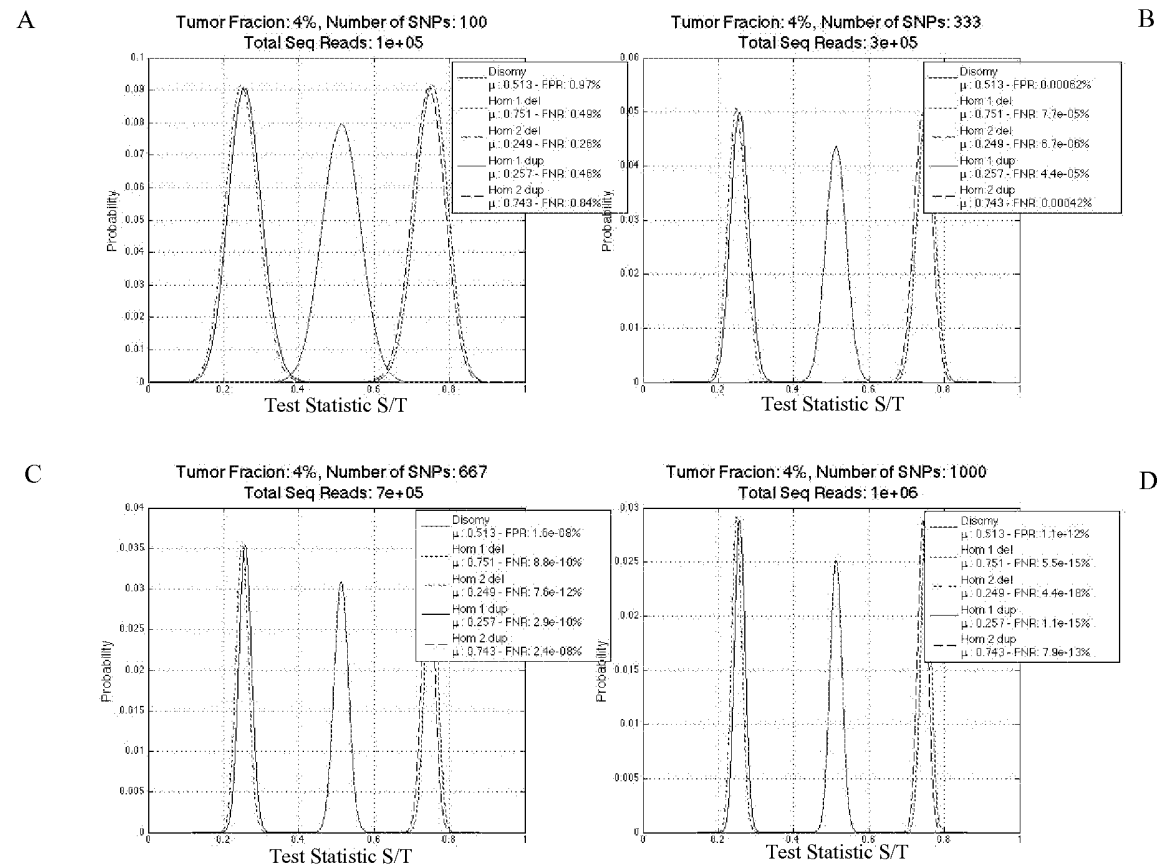
Figures 10A-10D

DOR of 1000 and Tumor Fraction of 3%:



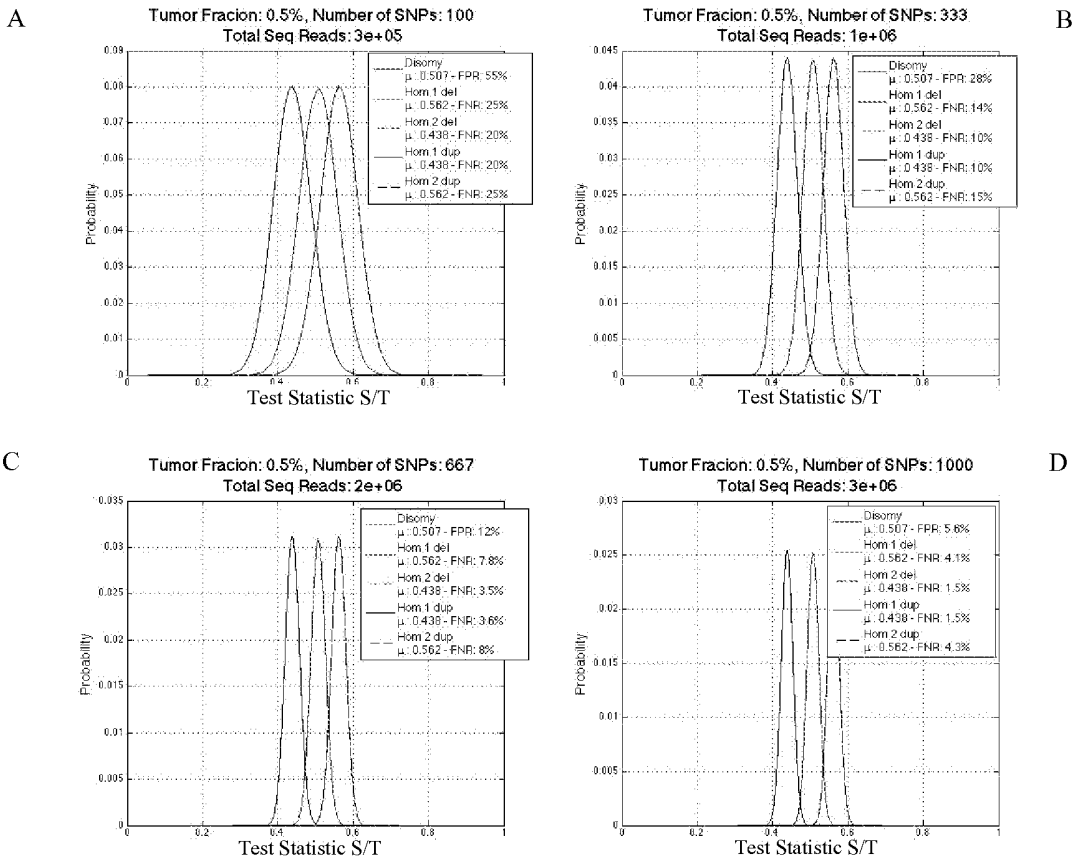
Figures 11A-11D

DOR of 1000 and Tumor Fraction of 4%:



Figures 12A-12D

DOR of 3000 and Tumor Fraction of 0.5%:



Figures 13A-13D

DOR of 3000 and Tumor Fraction of 1%:

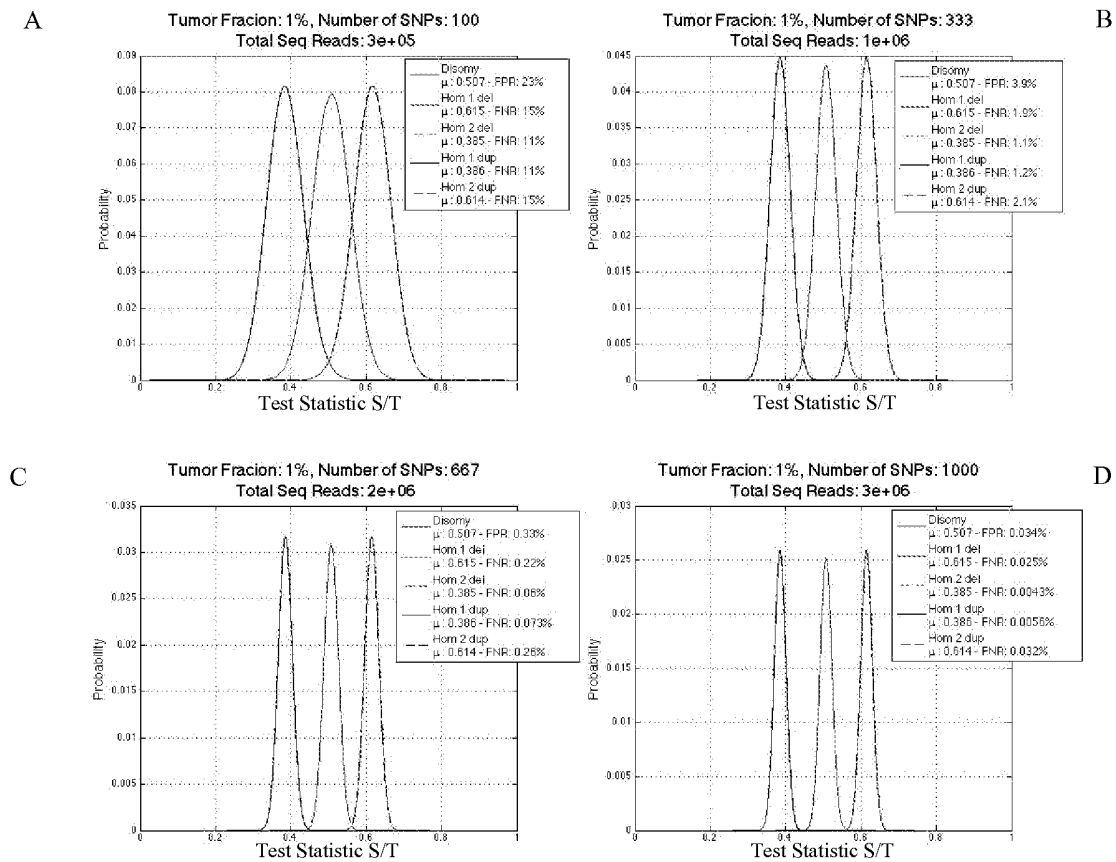
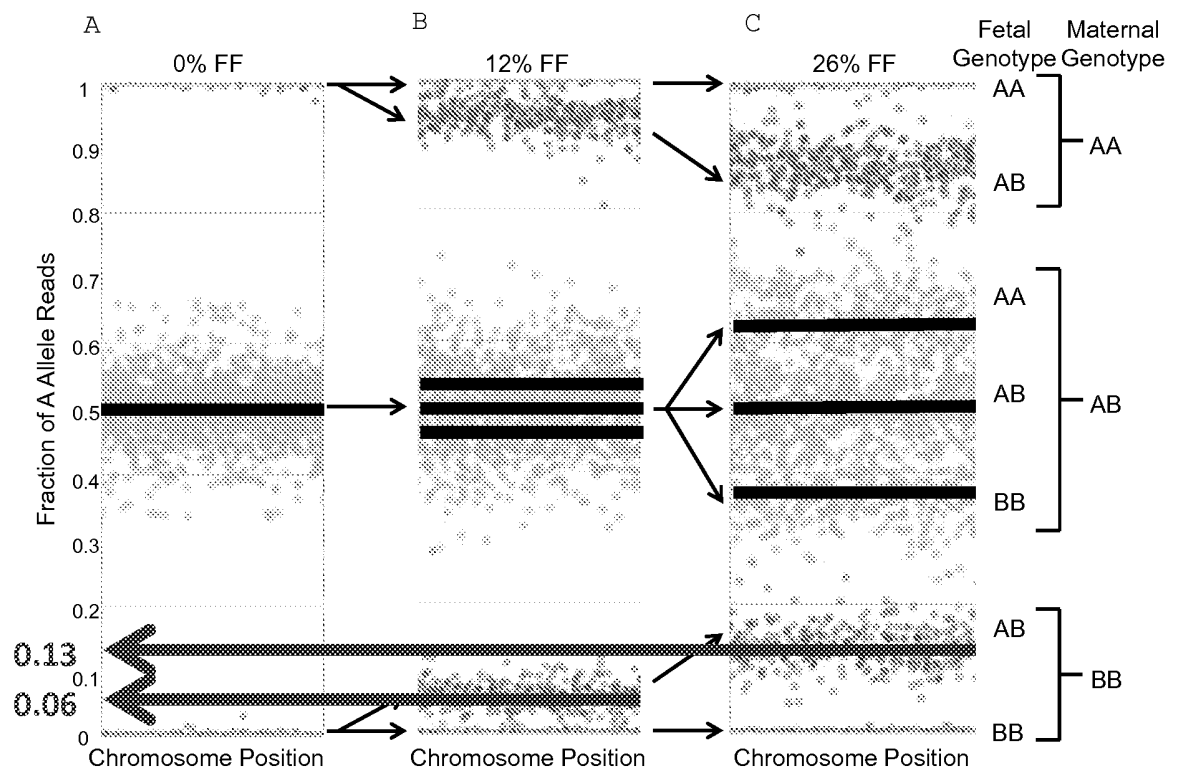


Figure 14

Syndrome	Sensitivity	Specificity
22q11.2 Deletion/ DiGeorge	97.8% (45/46) [CI: 88.5 – 99.95%]	99.2% (392/395) [CI: 97.8 - 99.8%]
Angelman	100% (21/21) [CI: 83.9 – 100%]	100% (418/418) [CI: 99.1 – 100%]
Cri du chat	100% (24/24) [CI: 85.7 – 100%]	99.8% (415/416) [CI: 98.7 – 99.99%]
Monosomy 1p36	100% (1/1) [CI: 2.5 – 100%]	100% (438/438) [CI: 99.2 – 100%]
Prader-Willi	100% (15/15) [CI: 78.2 – 100%]	100% (424/424) [CI: 99.1 – 100%]
Wolf-Hirschhorn	100% (2/2) [CI: 15.8 – 100%]	99.8% (437/438) [CI: 98.7 – 100%]

Figures 15A-15C

Allele Frequency Plots: Visualizing Data



Figures 16A and 16B

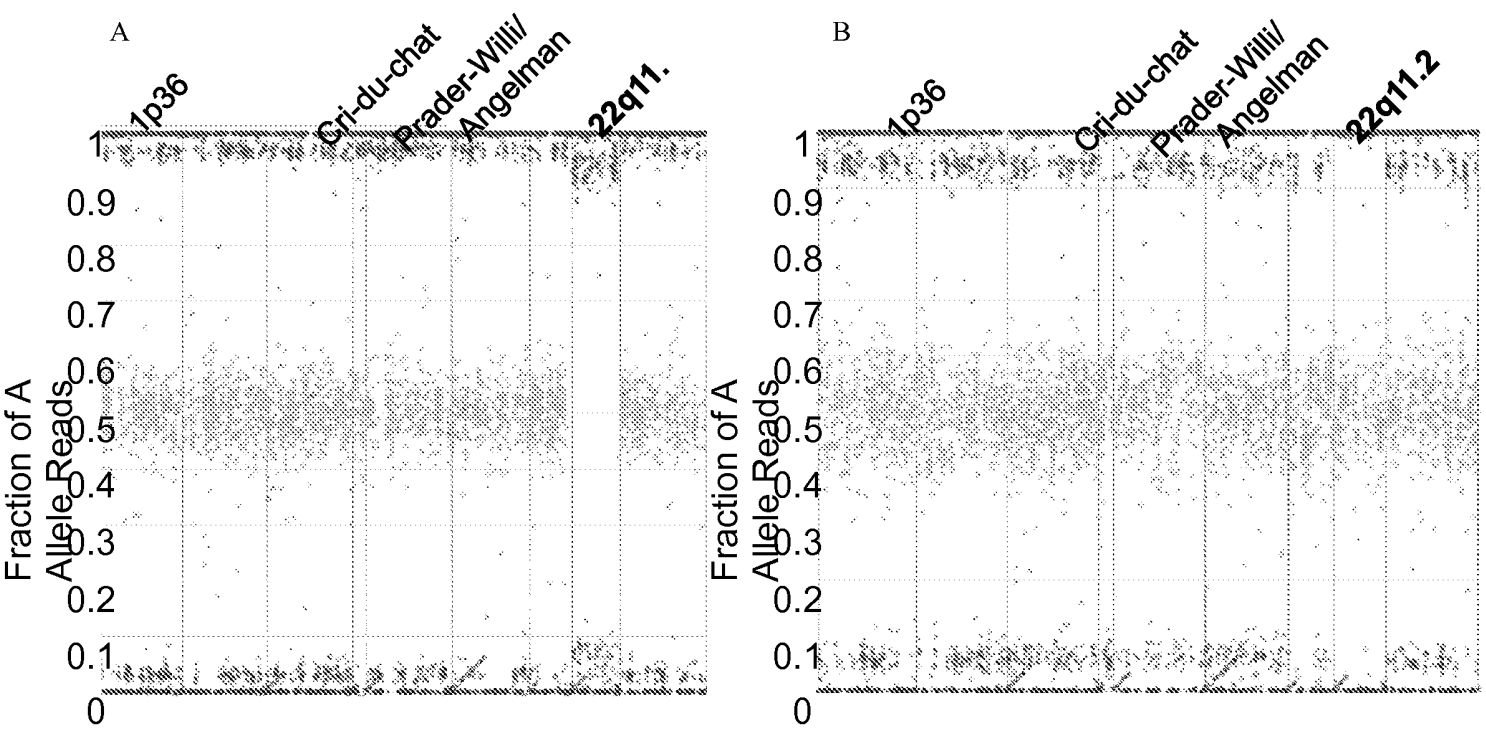


Figure 17

Maternally Inherited Cri-du-Chat Syndrome

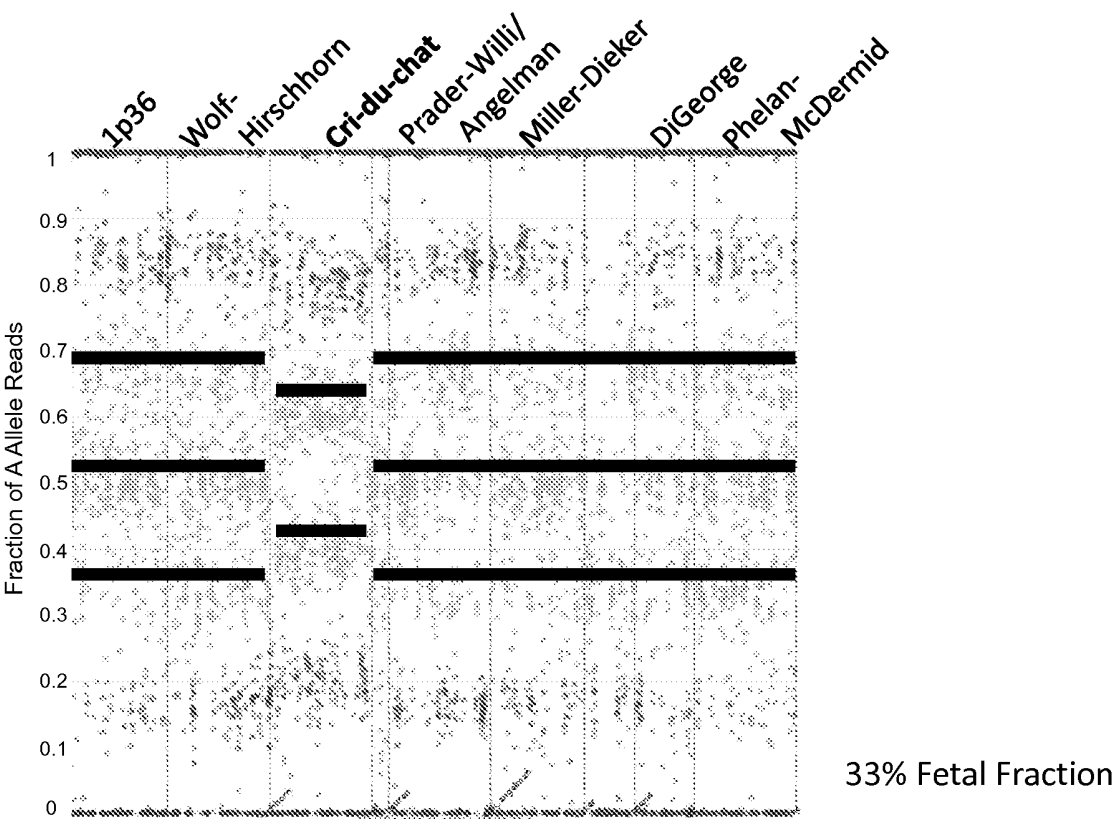


Figure 18

Paternally Inherited Wolf-Hirschhorn Syndrome

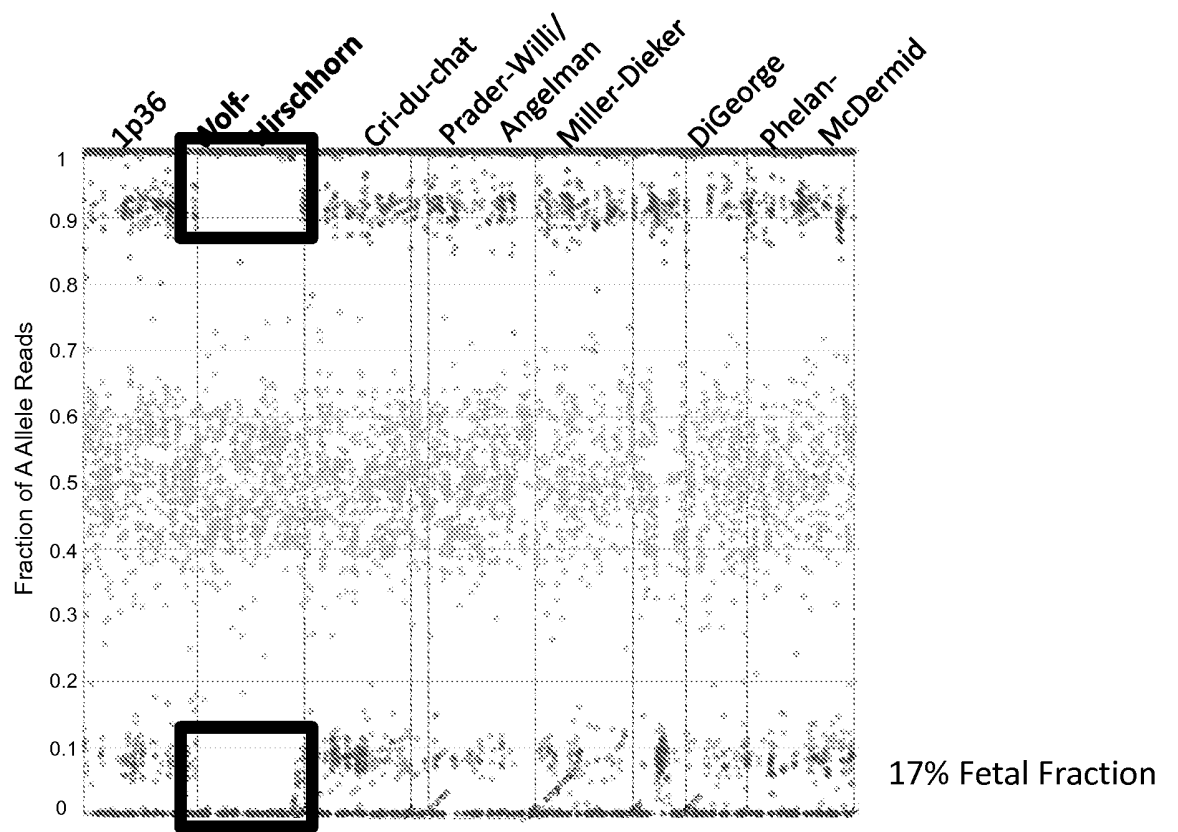


FIG. 19B 10% Father in Daughter

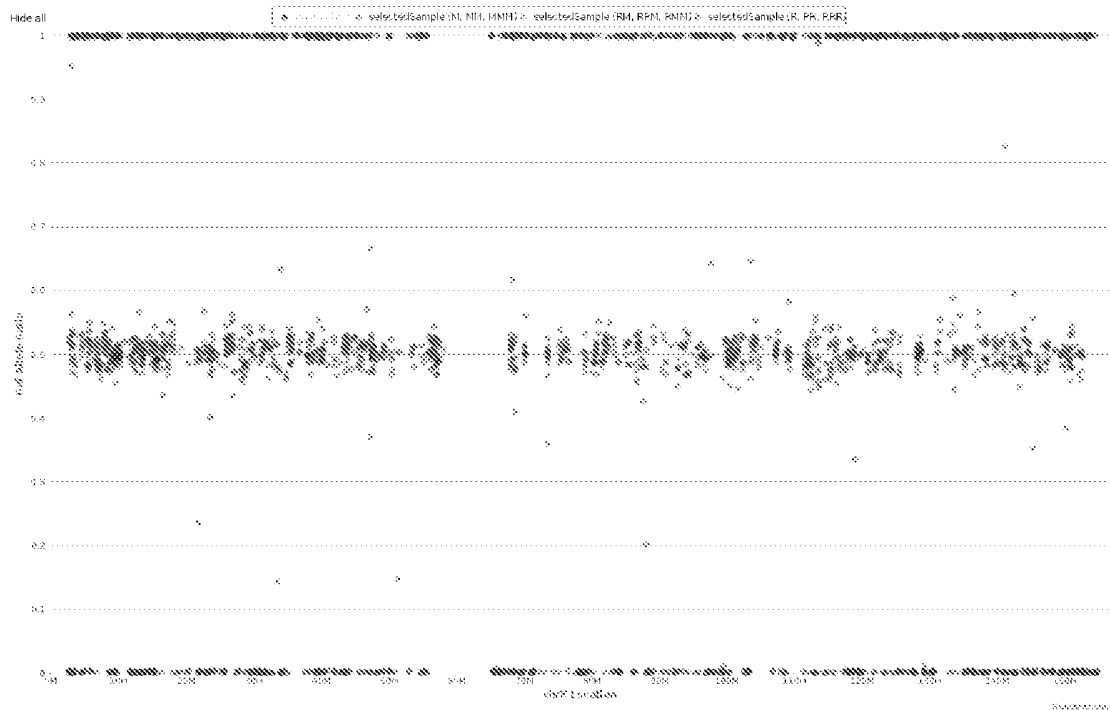
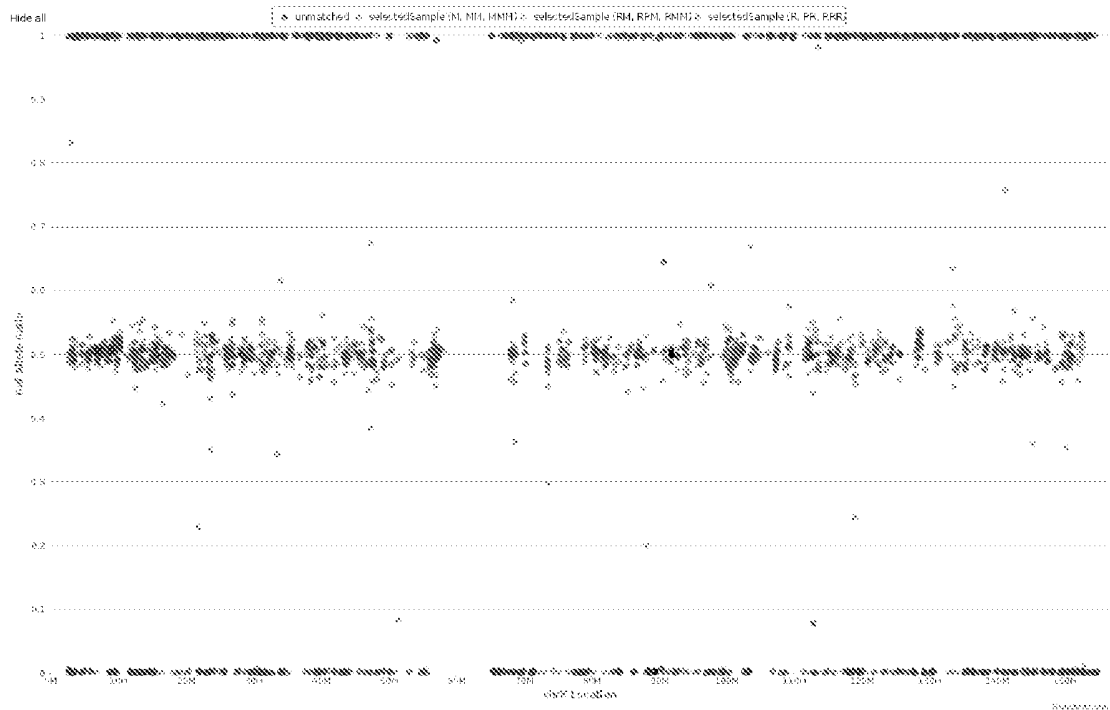
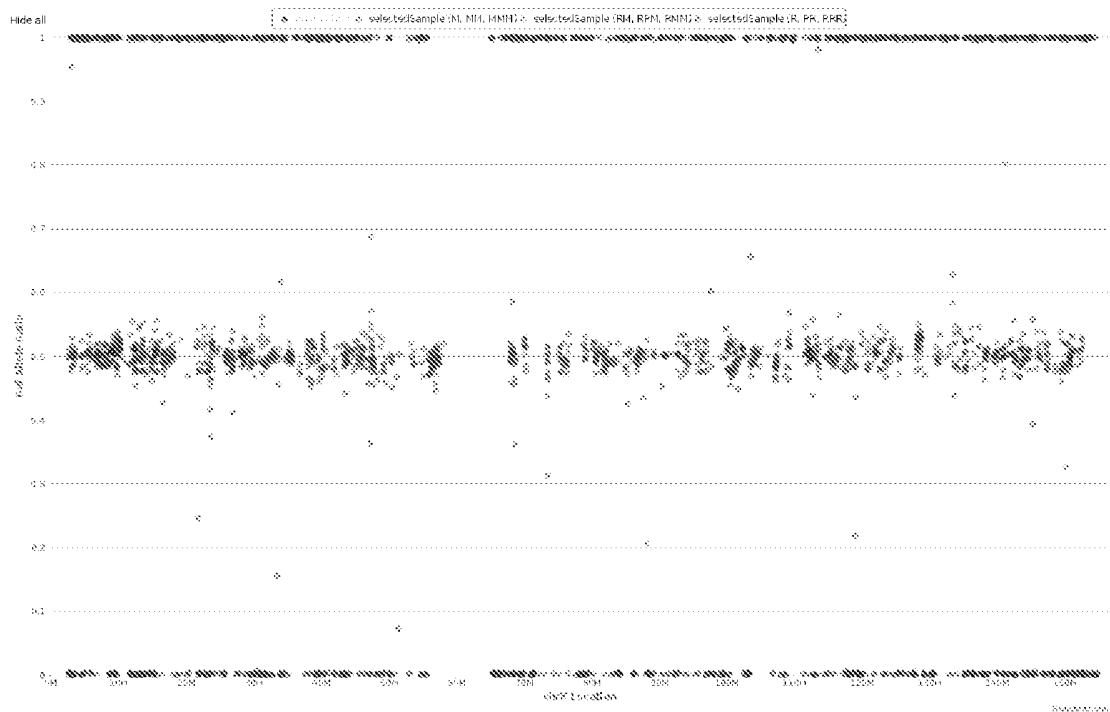
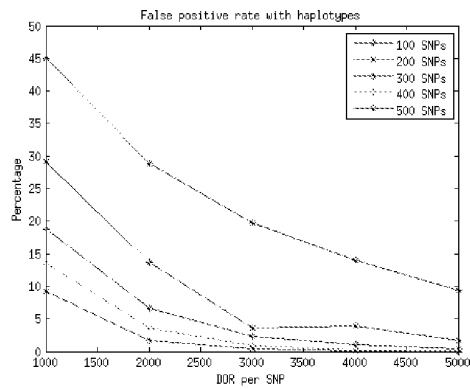


FIG. 19C 1% Father in Daughter

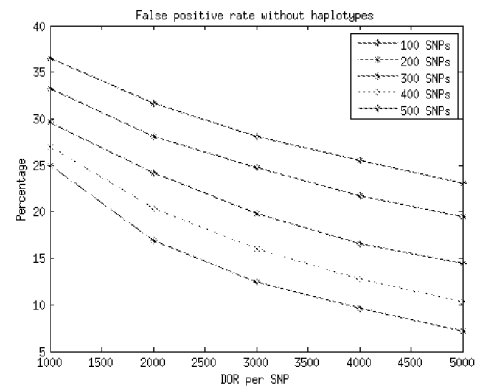




Figures 20A and 20B

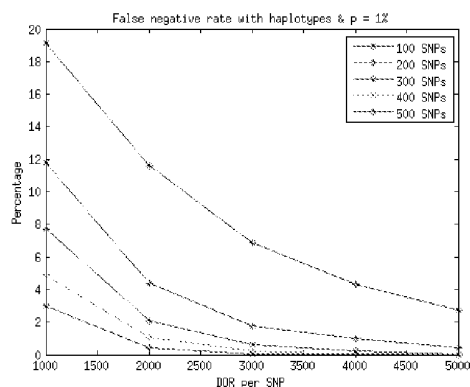


(a) With Haplotypes

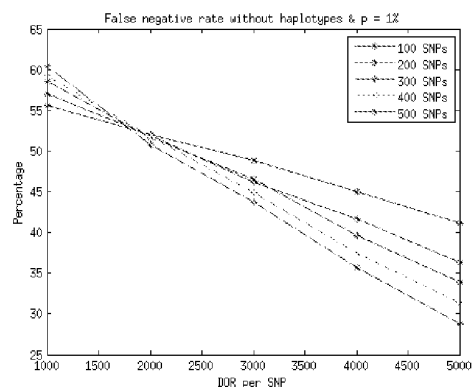


(b) Without Haplotypes

Figures 21A and 21B

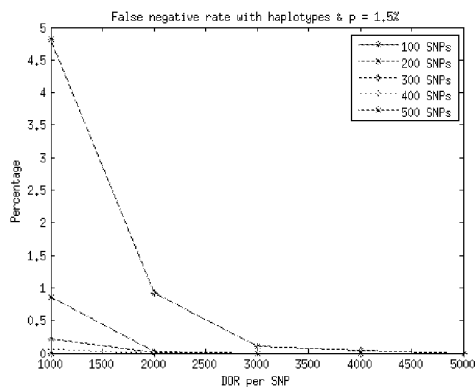


(a) With Haplotypes

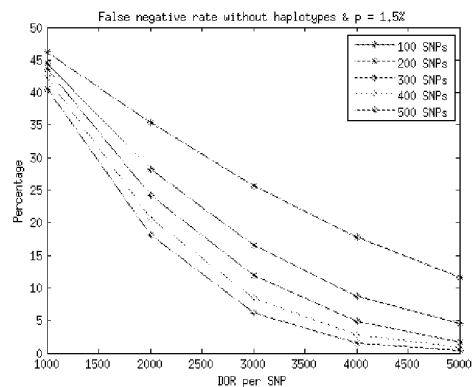


(b) Without Haplotypes

Figures 22A and 22B

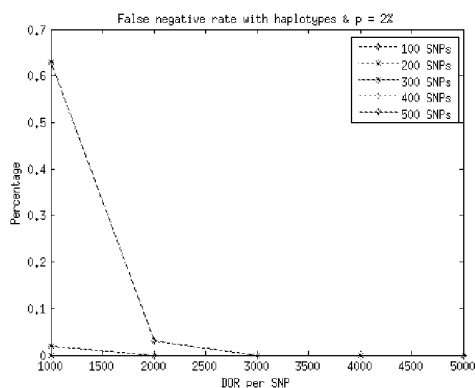


(a) With Haplotypes

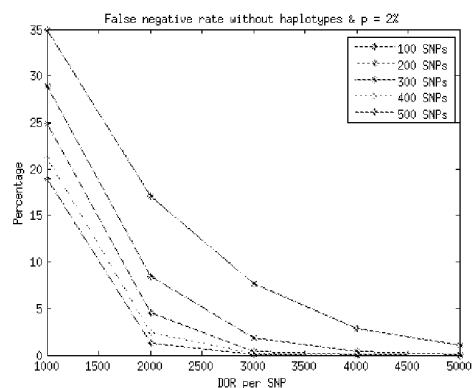


(b) Without Haplotypes

Figures 23A and 23B

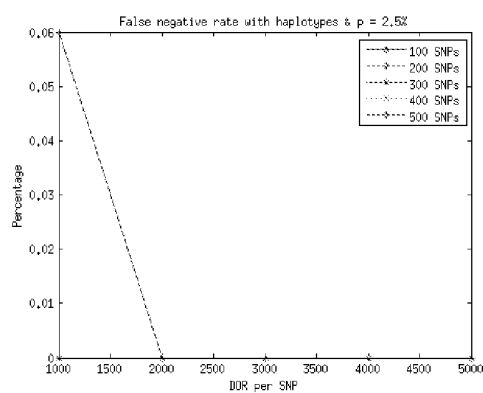


(a) With Haplotypes

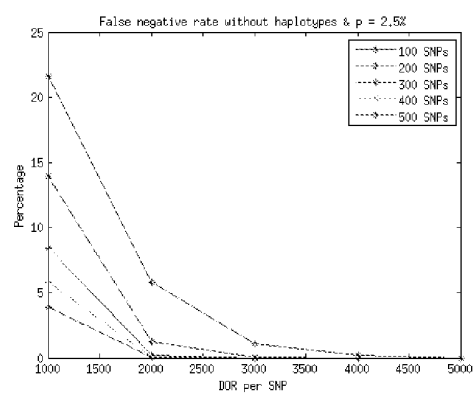


(b) Without Haplotypes

Figures 24A and 24B

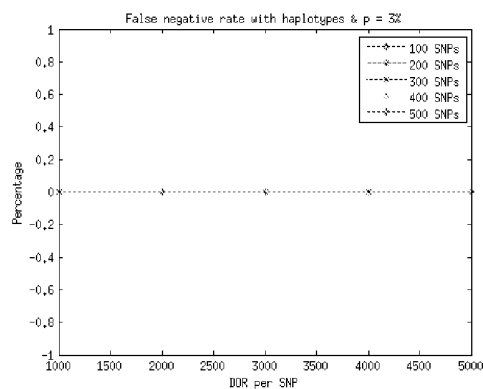


(a) With Haplotypes

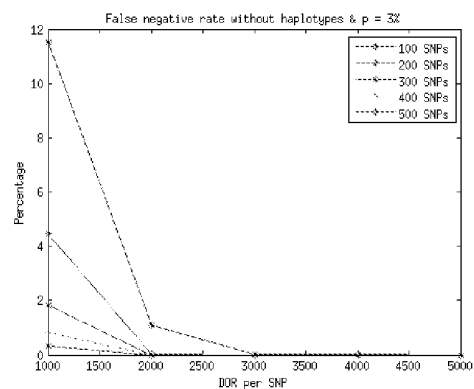


(b) Without Haplotypes

Figures 25A and 25B



(a) With Haplotypes



(b) Without Haplotypes

Figure 26

	S = 1000, D = 1000	S = 500, D = 1000	S = 1000, D = 500	S = 500, D = 500
With Phase	1.50%	8.80%	10.20%	22.30%
Without Phase	10.60%	10.80%	17.90%	20.80%

Figure 27

	S = 1000, D = 1000	S = 500, D = 1000	S = 1000, D = 500	S = 500, D = 500
$p = 1\%$, With Phase	0.00%	0.10%	3.00%	9.70%
$p = 1\%$, Without Phase	74.20%	73.70%	74.60%	76.00%
$p = 2\%$, With Phase	0.00%	0.00%	0.00%	0.00%
$p = 2\%$, Without Phase	13.90%	14.80%	41.00%	42.70%
$p = 3\%$, With Phase	0.00%	0.00%	0.00%	0.00%
$p = 3\%$, Without Phase	0.00%	0.00%	5.70%	5.00%
$p = 4\%$, With Phase	0.00%	0.00%	0.00%	0.00%
$p = 4\%$, Without Phase	0.00%	0.00%	0.00%	0.00%
$p = 5\%$, With Phase	0.00%	0.00%	0.00%	0.00%
$p = 5\%$, Without Phase	0.00%	0.00%	0.00%	0.00%