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Kung

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(54) **ELECTROMAGNETIC FIELD SOURCE DEVICE WITH DETECTION OF POSITION OF SECONDARY COIL IN RELATION TO MULTIPLE PRIMARY COILS**

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(21) Appl. No.: **09/697,338**

(22) Filed: **Oct. 26, 2000**

Related U.S. Application Data

(63) Continuation of application No. 09/304,198, filed on May 3, 1999, now Pat. No. 6,212,430.

(51) **Int. Cl.**[7] **A61N 1/00**
(52) **U.S. Cl.** **607/61**; 623/3.27
(58) **Field of Search** 607/30, 32, 33, 607/60, 61; 128/903; 623/3.27

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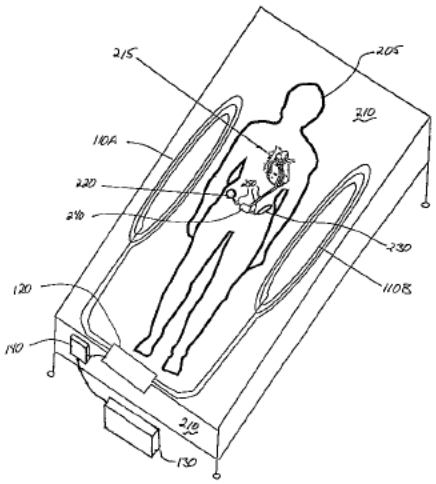
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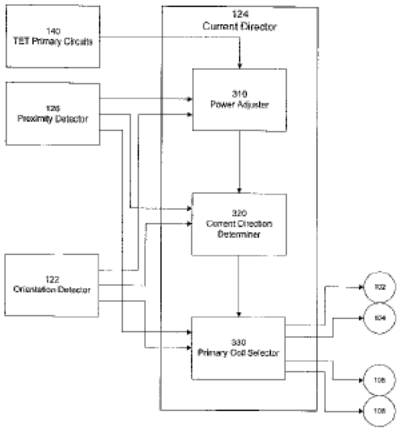
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(57) **ABSTRACT**

An electromagnetic field source (EFS) for providing electromagnetic energy to a secondary coil, including two or more primary coils that each carry a time-varying current to produce an electromagnetic field, and a controller that selectively provides current to one or more primary coils based on their position with respect to the secondary coil. The secondary coil may be implanted in a human recipient and used to provide power for the operation of a medical device, such as an artificial heart or ventricular assist device. The invention also provides such a secondary coil and EFS, collectively referred to as a transcutaneous energy transfer (TET) device. The primary coils of the EFS or TET may be housed in furniture. For example, they may be housed in a bed mattress or mattress pad on which the recipient rests, or in a blanket for covering the recipient. The controller includes a proximity detector that identifies those primary coils that are closest to the secondary coil, and a current director that, responsive to the proximity detector, selectively directs time-varying currents through the closest primary coils. The controller may also include an orientation detector, coupled to the current director, that determines an orientation of the secondary coil with respect to the closest primary coils. In one implementation, the proximity detector identifies the quantity of closest primary coils utilizing a resonance frequency shift detector that detects a shift in inductance of one or more primary coils due to the proximity of the secondary coil.

28 Claims, 10 Drawing Sheets





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FIGURE 1

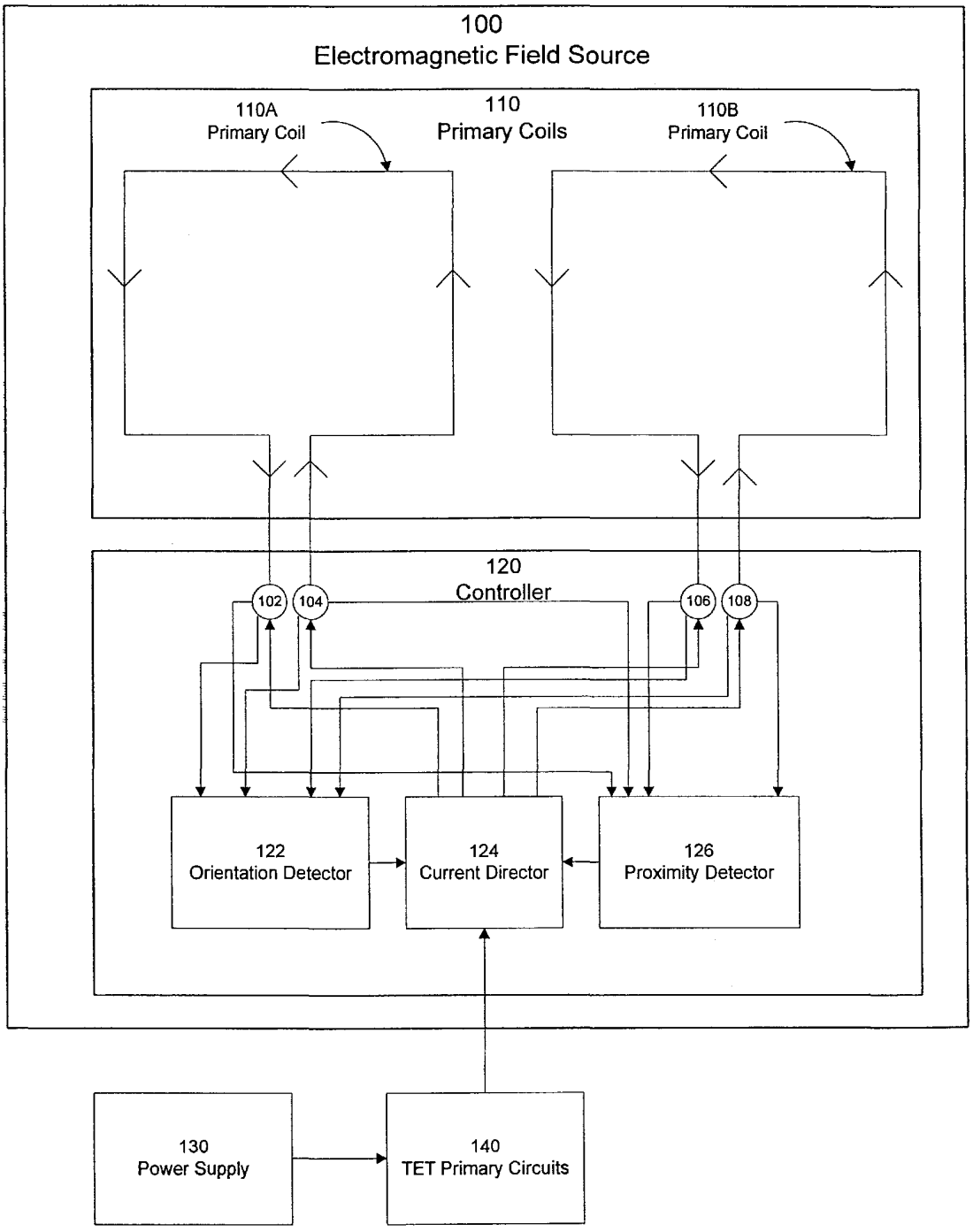

100
Electromagnetic Field Source
110A
Primary Coil
110
Primary Coils
110B
Primary Coil
120
Controller
102
104
106
108
122
Orientation Detector
124
Current Director
126
Proximity Detector
130
Power Supply
140
TET Primary Circuits

FIGURE 2

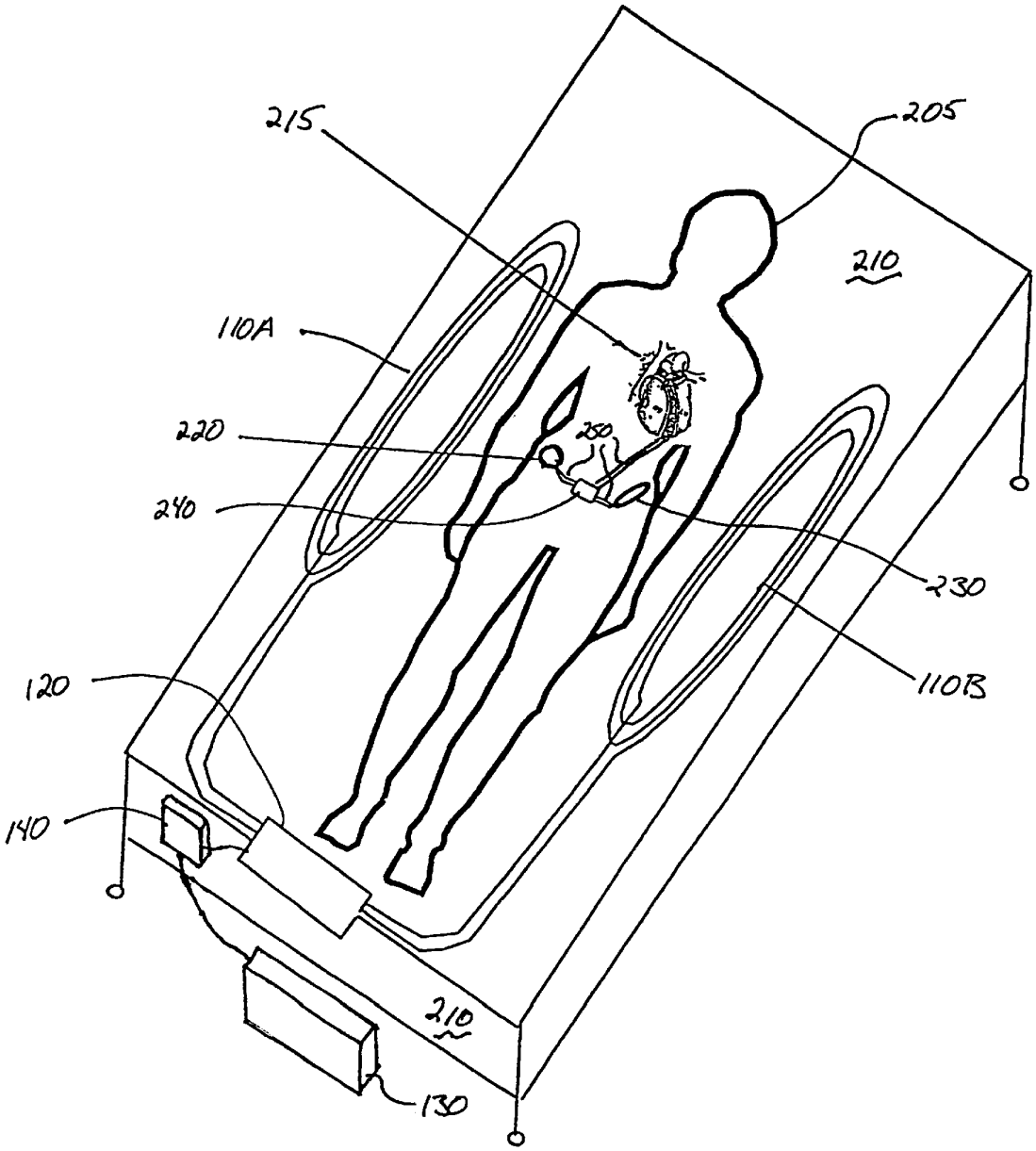


FIGURE 3

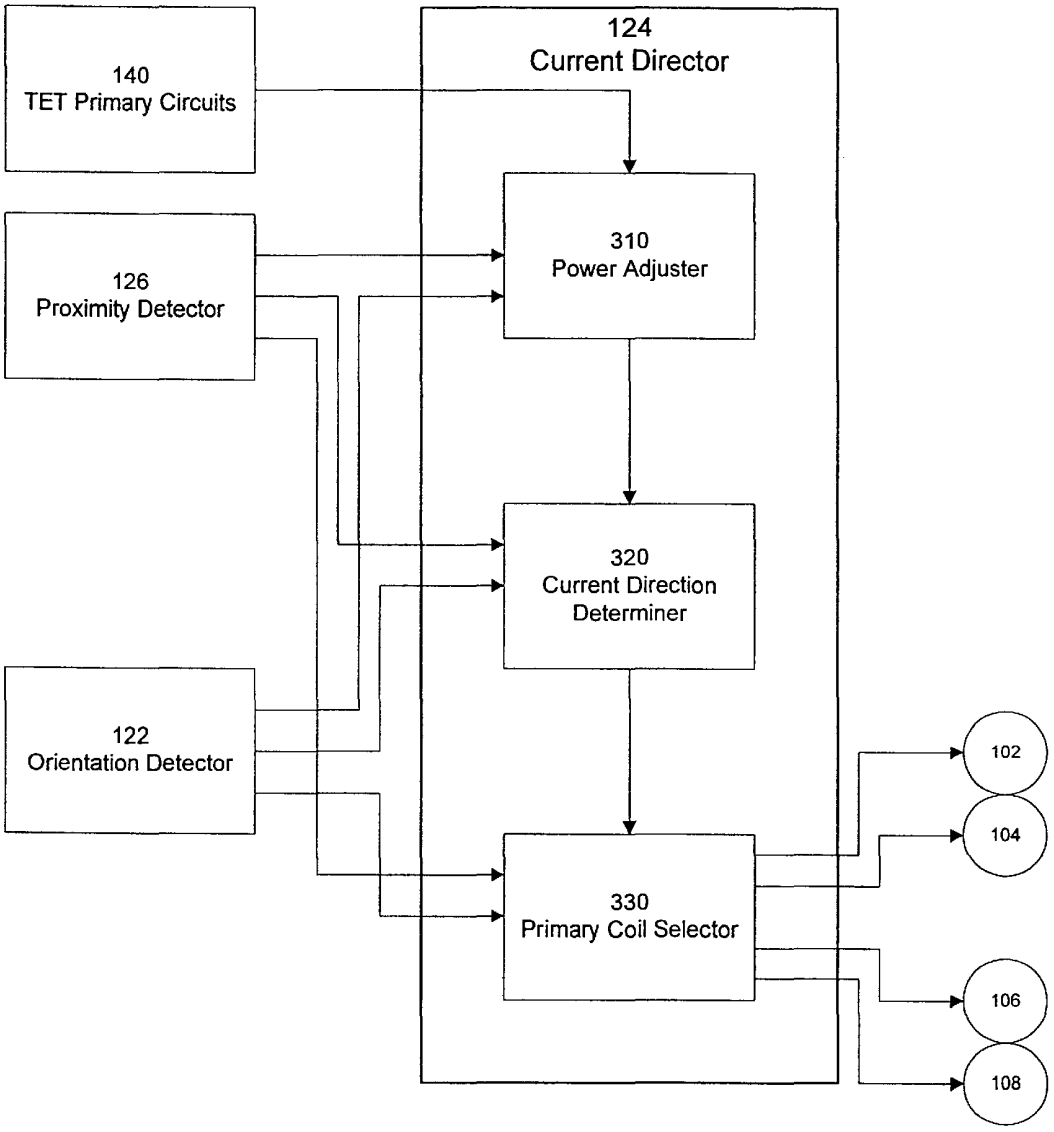

140
TET Primary Circuits
124
Current Director
126
Proximity Detector
310
Power Adjuster
320
Current Direction
Determiner
122
Orientation Detector
330
Primary Coil Selector
102
104
106
108

FIGURE 4A

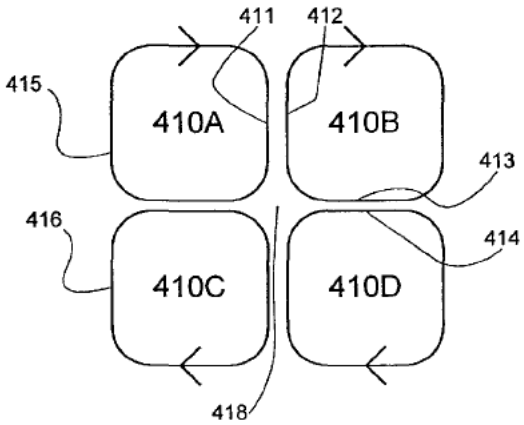


FIGURE 4B

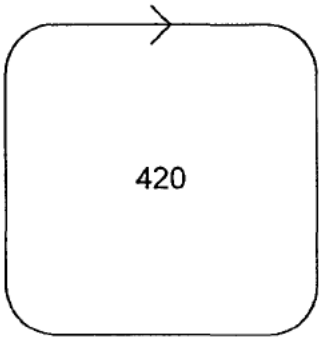


FIGURE 4C

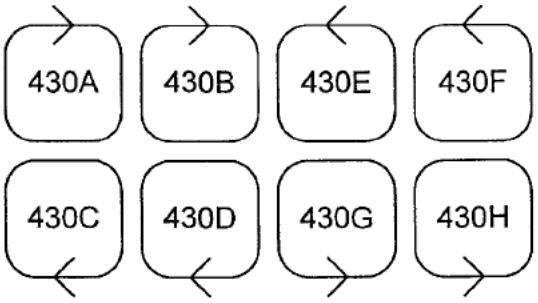


FIGURE 4D

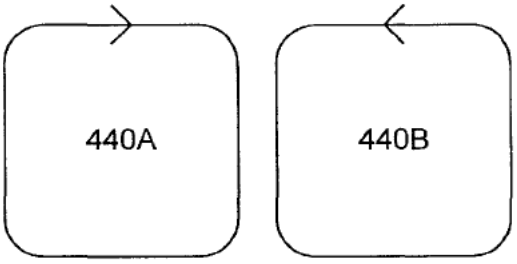


FIGURE 5A

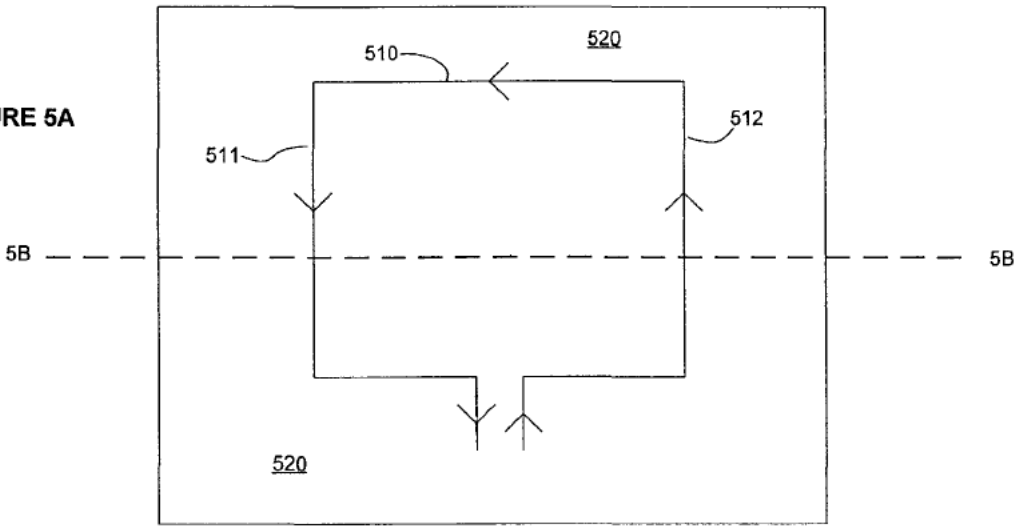


FIGURE 5B

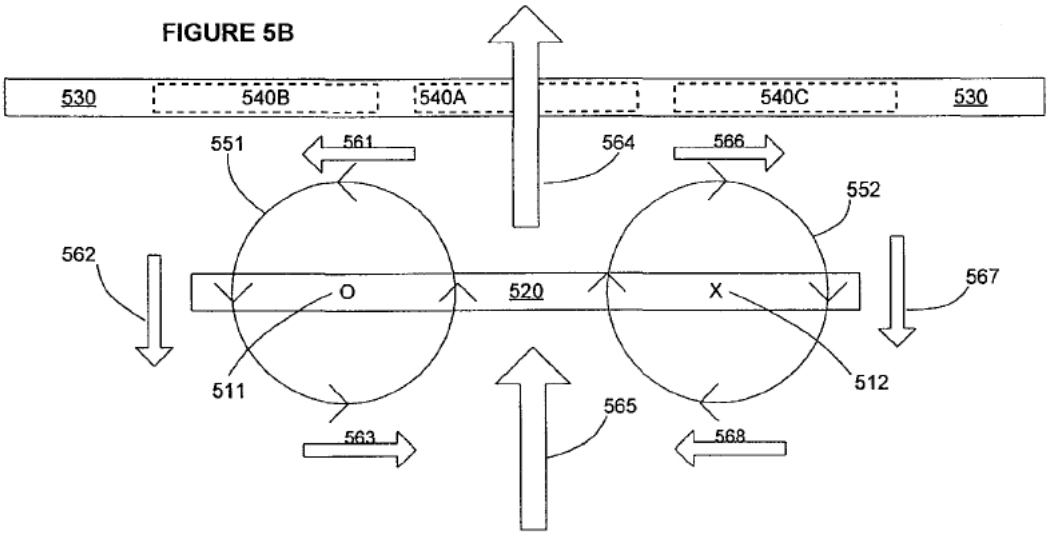


FIGURE 6A

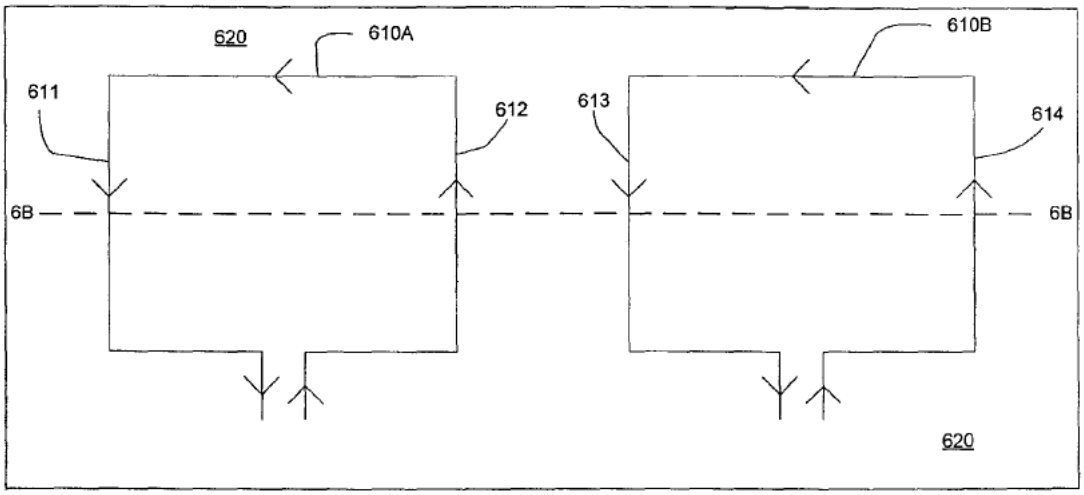


FIGURE 6B

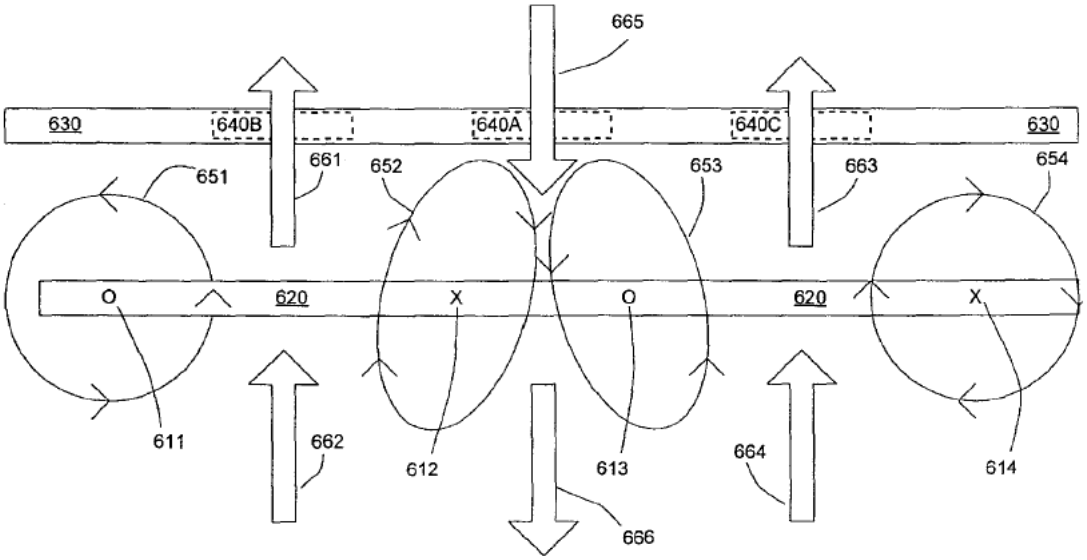
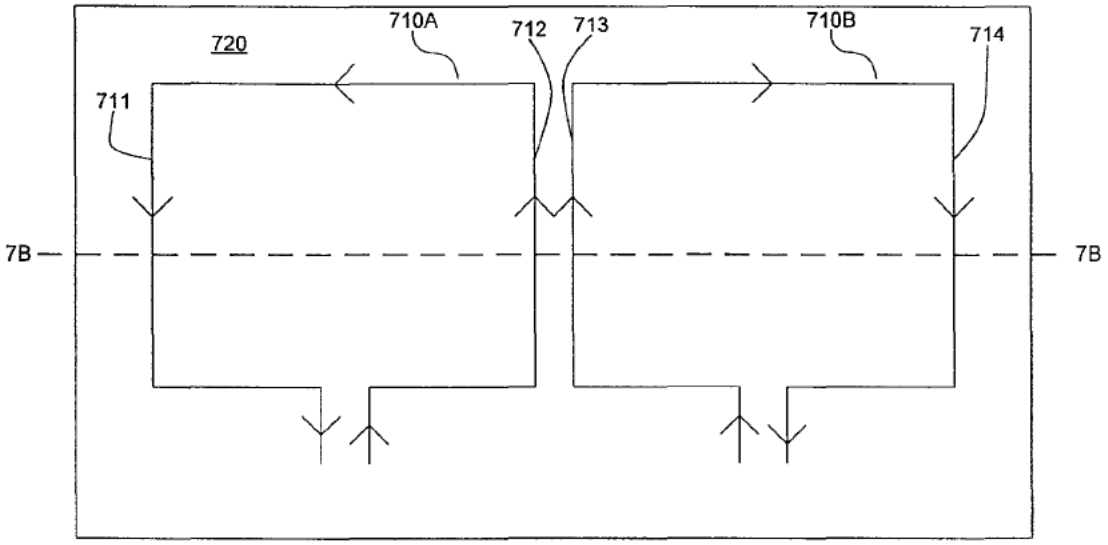


FIGURE 7A



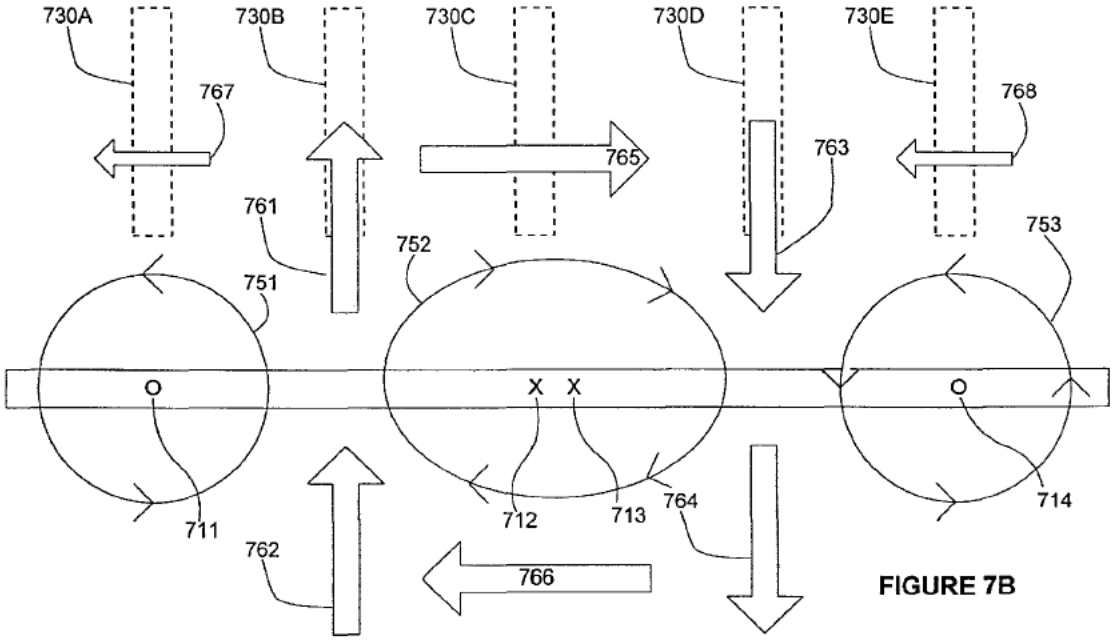


FIGURE 7B

FIGURE 8A

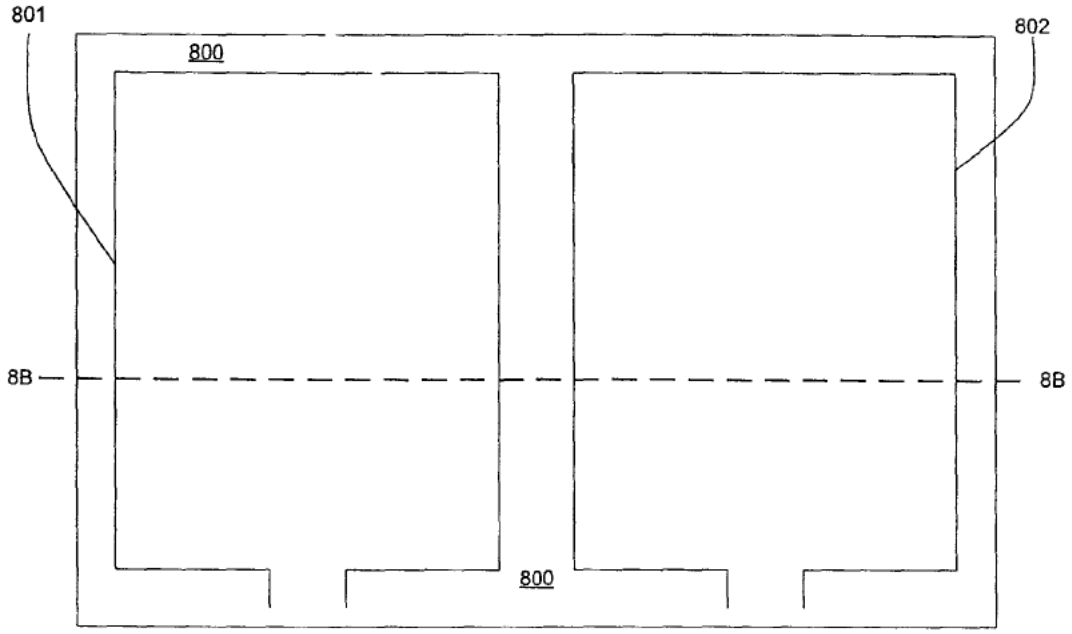


FIGURE 8B

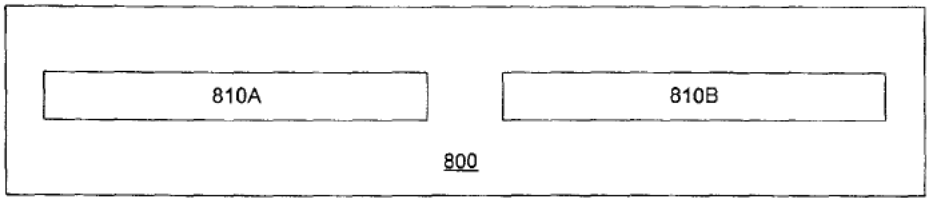


FIGURE 8C

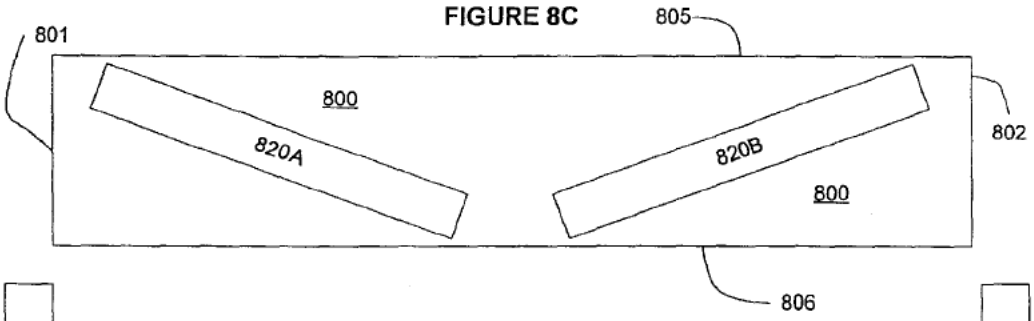


FIGURE 8D

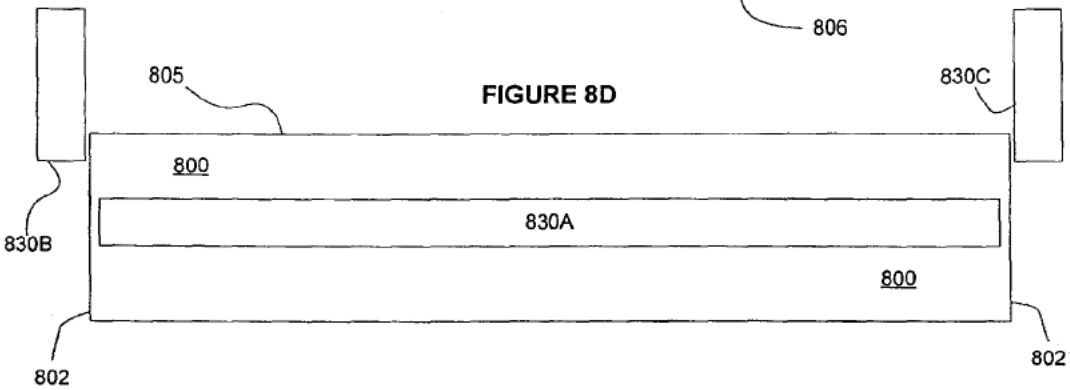
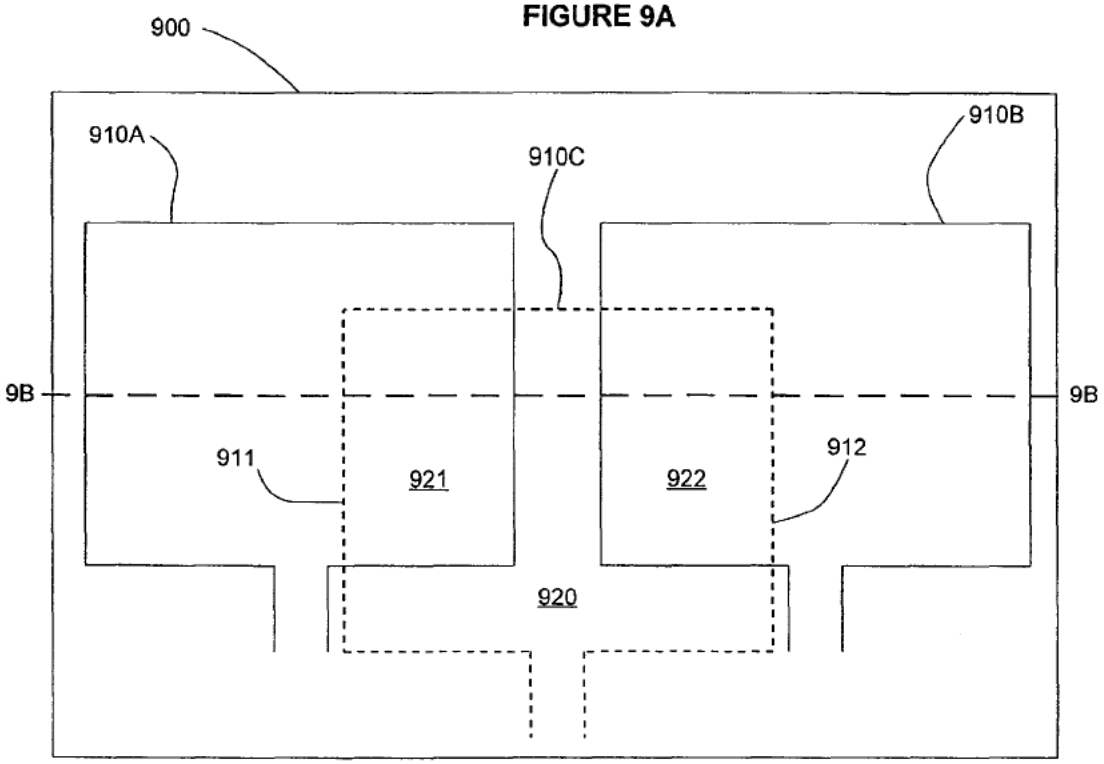


FIGURE 9A



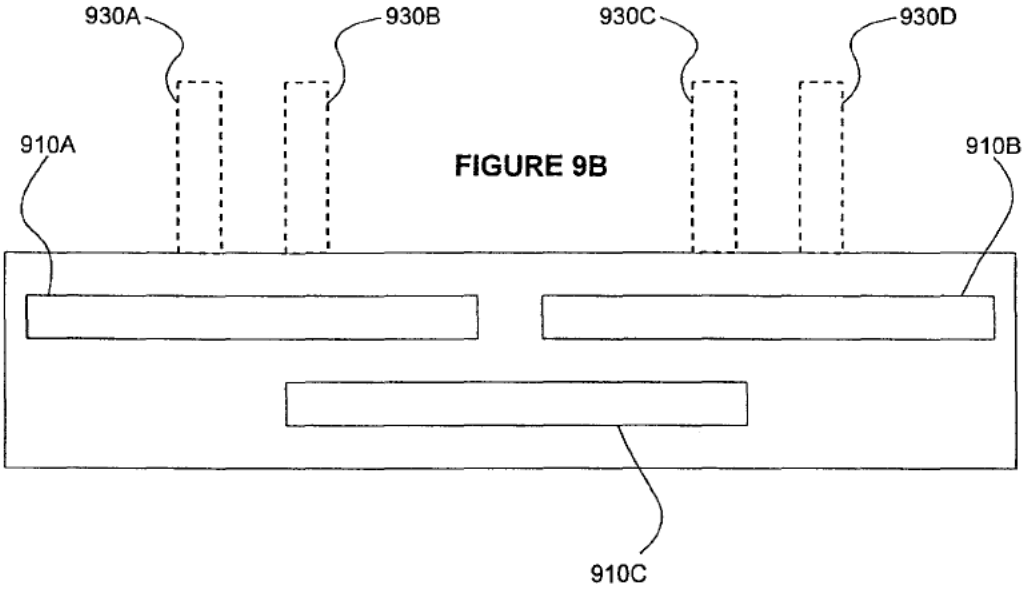
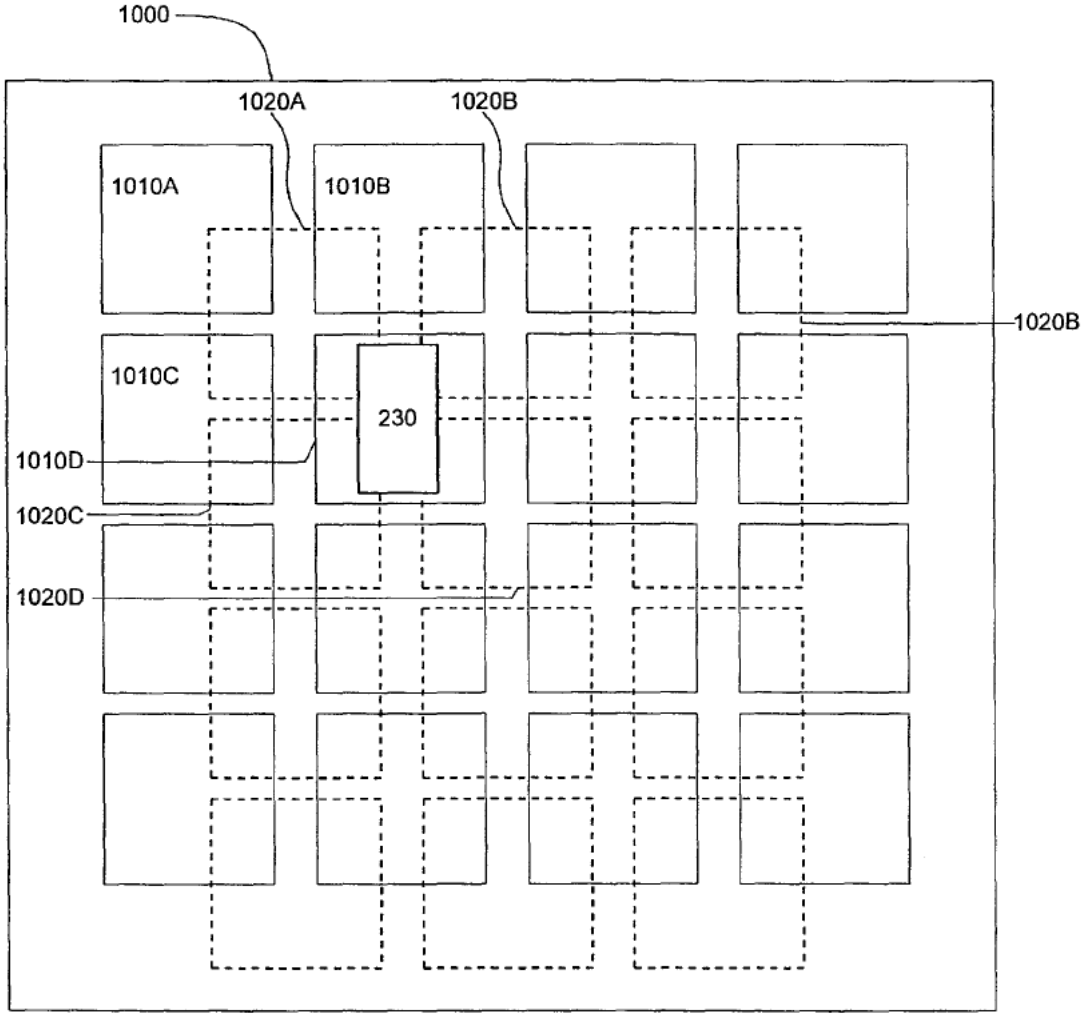


FIGURE 9B

FIGURE 10


1000
1020A
1020B
1010A
1010B
1020B
1010C
230
1010D
1020C
1020D

ELECTROMAGNETIC FIELD SOURCE DEVICE WITH DETECTION OF POSITION OF SECONDARY COIL IN RELATION TO MULTIPLE PRIMARY COILS

RELATED APPLICATIONS

This application is a continuation of application Ser. No. 09/304,198, filed on May 3, 1999, now U.S. Pat. No. 6,212,430 and titled "Electromagnetic Field Source with Detection of Position of Secondary Coil in Relation to Multiple Primary Coils."

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to energy transfer devices and methods and, more particularly, to devices and processes for transcutaneous energy transfer (TET) to a secondary coil implanted in a subject.

2. Related Art

Many medical devices are now designed to be implanted in humans or animals, including pacemakers, defibrillators, circulatory assist devices, cardiac replacement devices such as artificial hearts, cochler implants, neuromuscular simulators, biosensors, and the like. Since many of these devices require a source of power, inductively coupled transcutaneous energy transfer (TET) systems are coming into increasing use. A TET system may be employed to supplement, replace, or charge an implanted power source, such as a rechargeable battery. Unlike other types of power transfer systems, TET systems have an advantage of being able to provide power to the implanted electrical and/or mechanical device, or recharge the internal power source, without puncturing the skin. Thus, possibilities of infection are reduced and comfort and convenience are increased.

TET devices include an external primary coil and an implanted secondary coil, separated by intervening layers of tissue. The two coils constitute a transcutaneous transformer. The transformer is designed to induce alternating current in the subcutaneous secondary coil, typically for transformation to direct current to power the implanted device. TET devices therefore also typically include an oscillator and other electrical circuits for periodically providing appropriate alternating current to the primary coil. These circuits, referred to for convenience herein as "TET primary circuits," receive their power from an external power source.

Generally, the non-implanted portions of conventional TET systems are attached externally to the patient, typically by a belt or other fastener or garment, such that the primary coil of the TET is operationally aligned with the implanted secondary coil. The TET primary circuits and external power supply are also generally attached to the patient's body at or near the site of the attachment of the primary coil. Such a configuration typically is disadvantageous, however, particularly when the patient is sleeping or resting. For example, if a patient is sleeping on a mattress, the patient would likely be uncomfortable, or restricted in movement, if all or some of the TET primary circuits and external power supply were attached to the patient. In addition to discomfort or restriction of movement, additional disadvantages of such body attachments include possibilities of injury to the patient or the devices. Movements of the patient may alter the position of the primary coil so that it is not properly positioned over the implanted secondary coil to achieve a desired or required transfer of power.

To overcome these drawbacks, other conventional approaches require only the primary coil be attached to the patient. Wires connect the primary coil to the TET primary circuits, which, with the power supply, may be located at a distance from the patient outside of the sleeping or resting surface. However, such an alternative configuration also has significant disadvantages. First, the primary coil is still attached to the patient and therefore subject to the above drawbacks may cause discomfort or restriction of movement. Also, as the patient moves, the wires connecting the externally attached primary coil to the TET primary circuits may become tangled or entangled with bedding or the patient. In addition to being uncomfortable, such tangling may result in dislodging the primary coil from its required alignment; it may injure the patient, such as by restricting blood or oxygen supply; or it may interfere with tubes or other devices attached to the patient.

SUMMARY

To overcome the above and other drawbacks to conventional systems, the present invention provides an electromagnetic field source (EFS) for providing electromagnetic energy to a secondary coil. In one embodiment, the EFS includes two or more primary coils that each carry a time-varying current to produce an electromagnetic field. The EFS also includes a controller that selectively provides current to one or more of the primary coils based on their position relative to the secondary coil. The controller may be implemented in electrical circuits, software, firmware, or any combination thereof.

In another embodiment, the invention provides a transcutaneous energy transmission (TET) device including a secondary coil implanted in a human being. In this embodiment, the secondary coil is used to provide power for the operation of an implanted medical device, such as an artificial heart or ventricular assist device. In some implementations, the primary coils are housed in furniture, such as a bed mattress. Also, the primary coils may be housed in bed covering, such as a blanket or mattress pad.

In certain embodiments the controller includes a proximity detector that identifies a quantity of primary coils that are closest to the secondary coil, referred herein to as the "closest" primary coils. A current director that is responsive to the proximity detector is also included in the controller. The current director selectively directs time-varying currents through the closest primary coils.

One advantage of a TET in accordance with certain aspects of the present invention is that there are no wires connecting the subject of the implanted device to external components, such as a power supply or other electrical circuits. Rather, a recipient of the implanted device may rest on furniture that houses the primary coils, and those primary coils that are closest to the implanted secondary coil may be energized. Thus, the recipient is uninhibited with respect to movement on or in the furniture, such as a bed, couch, or chair, and is provided with a more comfortable resting environment. Also, serious disadvantages of known systems, such as becoming entangled with a wire, or of dislodging a primary coil, are avoided by the present invention.

Another advantage is the portability of implementations such as those in which the primary coils are housed in a bed covering or a mattress pad. Thus, a recipient may pack such housing, together with the controller and power supply, in suitcases or similar containers for traveling. Similarly, a hospital mattress may readily be converted to include portions of a TET by covering it with a blanket or mattress pad containing primary coils in accordance with embodiments of the present invention.

Advantageously, the primary coils may be disposed over substantially all of the top surface of the mattress, or throughout the bed covering or mattress pad. Thus, in such embodiments, if the recipient shifts position on the mattress, there will be one or more primary coils located close to the implanted secondary coil. In some implementations, the primary coils may be positioned in generally even rows and columns with respect to the top surface of the mattress. In other implementations, they may be positioned generally in hexagonal arrangements. It will be understood to those of ordinary skill that there are many possible configurations that provide primary coils over the entire surface upon which the recipient is resting or reclining.

Also advantageously the controller of the EFS or TET may determine the approximate distance between the primary coils and the secondary coil, and adjust the amount of current to the closest primary coils accordingly. In particular, a proximity detector may be included to determine an approximate distance between one or more of the closest primary coils and the secondary coil. In embodiments that include such a proximity detector, if that distance is greater than a nominal threshold value, current director may increase the currents through selected ones of the closest primary coils. For example, if the recipient is sleeping on a pillow or is otherwise raised above the mattress, the distance from the implanted secondary coil to the primary coils in the mattress may be greater than normal (i.e., greater than when the recipient is sleeping directly on the mattress). By increasing the amount of current directed to the closest primary coils, the electromagnetic fields of the closest primary coils are increased to reach the secondary coil so that it may provide power to the medical device or to an energy storage device. In one embodiment of the EFS or TET, the proximity detector identifies a predetermined number of the closest primary coils. Alternatively, the quantity of closest primary coils may be identified by the proximity detector based on the size of the secondary coil.

The primary coils may be disposed in their housings in accordance with a wide variety of geometric schemes or arrangements. For example, the primary coils may be disposed in a single plane, or in two or more parallel planes. It should be understood that the specification herein of this, and other, geometric arrangements may be approximate. For example, it generally is not required that the primary coils be disposed precisely in a single or parallel planes, in precisely a square pattern, and so on. Rather, they may be approximately so disposed. Similarly, a second-layer primary coil need not be precisely aligned with first-layer primary coils, as described below.

In one embodiment in which a configuration of two parallel planes is used, dead zones of electromagnetic fields generated by one or more primary coils of a first plane are encompassed by electromagnetic fields generated by primary coils in a second plane that is parallel to the first plane. The term "dead zone" is used herein to refer to a space in which an electromagnetic field generated by a primary coil is not effective in energizing a secondary coil disposed in that space. This term is further explained, and is illustrated, below. The word "energize," and its grammatical variants, is used herein to refer to the provision of current to a primary coil so that it produces an electromagnetic field. The word "encompassed" is used herein in this context to refer to the covering of the dead zone by the electromagnetic field of a second layer of primary coils, such that the electromagnetic field is effective in energizing the secondary coil disposed in the dead zone of a first layer of primary coils.

In some embodiments having primary coils disposed in two parallel planes, a first plane includes two or more mutually adjacent first-plane primary coils. The term "mutually adjacent" means that each of two or more primary coils in a group is adjacent to each of the other primary coils in that group. Examples of such arrangements are the placement of the centers of the primary coils at the comers of a rectangular or triangular shape in the first plane. In such embodiments, a second plane is provided that has at least one second-plane primary coil (not to be confused with a secondary coil). These coils are positioned so that the projection of a magnetic center of the second-plane primary coil on the first plane is approximately equidistant from magnetic centers of each of the two or more mutually adjacent first-plane primary coils. For example, if first-plane square primary coils are positioned so that their comers are adjacent to each other, then a second-plane primary coil is placed in the second plane such that the projection of its magnetic center onto the first plane aligns with the comers of the first-plane square. The term "magnetic center" of a coil is used herein to mean the geometric center of isomagnetic contours representing the magnetic field generated by the coil. In a particular implementation of such an arrangement, the first plane has four mutually adjacent primary coils positioned in a roughly square arrangement. The second plane has one primary coil positioned so that the projection of its geometric center on the first plane is approximately centrally located among the four first-plane primary coils.

In some embodiments, the EFS or TET also includes an orientation detector, coupled to the current director, that determines the orientation of the plane of the secondary coil with respect to the planes of the closest primary coils. In some implementations, the orientation detector is electrically coupled to the primary coils and determines the orientation of the plane of the secondary coil utilizing a resonance frequency shift detector. The detector compares shifts in inductance of two or more primary coils due to the proximity of the secondary coil. In other implementations, the orientation detector may determine the plane of the secondary coil utilizing an optical sensor, a mechanical sensor, electromagnetic transmission, or any combination of these or other sensors now or later developed.

In some embodiments, if the orientation detector determines that the secondary coil is disposed in a plane predominantly parallel to the planes of the closest primary coils, the current director directs time-varying currents to flow through the closest primary coils so that each current flows in the same direction. In one implementation of such an embodiment, the quantity of closest primary coils may be simple one coil. In particular, there may be a single closest primary coil if the proximity detector determines that the secondary coil is proximate to an electromagnetic field of the one closest primary coil, not including a dead zone. In another implementation, the quantity of closest primary coils is two or more when all of the primary coils are disposed in the same plane and the proximity detector determines that the secondary coil is proximate to a dead zone of the one closest primary coil.

If the orientation detector determines that the secondary coil is disposed in a plane predominantly perpendicular to the planes of the closest primary coils, the current director directs time-varying currents to flow through the closest primary coils so that a current in each closest primary coil flows in a direction opposite to a direction of a current in an adjacent closest primary coil. In one implementation in which the secondary coil is perpendicularly positioned, the quantity of closest primary coils is two.

The EFS may also include a power supply that is coupled to the controller and that provides current to the primary

coils. It should be understood that the power supply may not be directly coupled to the primary coils, but that intermediary components, such as a regulator, may be present. Alternatively, the regulator or other components may be included in the power supply.

In further embodiments, the invention provides a method for providing electromagnetic energy to a secondary coil. The method includes disposing primary coils, each constructed and arranged to carry a time-varying current to produce an electromagnetic field, and selectively providing current to the primary coils based on their position with respect to the secondary coil. In some implementations, such selection includes identifying a quantity of the primary coils that are closest to the secondary coil, and selectively directing time-varying currents through the closest primary coils.

In other embodiments, the invention is a cardiac-assist device including pumping means and a transcutaneous energy transmission (TET) device. The TET includes a secondary coil implanted in a subject, primary coils that carry a time-varying current to produce an electromagnetic field, and a controller that selectively provides current to one or more of the primary coils based on their position with respect to the secondary coil. The pumping means may include a total artificial heart or a ventricular assist device. More generally, the invention provides in some embodiments an organ-assist device including such a TET and an internally implanted organ-assist component.

In yet further embodiments, the invention is an article of furniture having embedded in it two or more primary coils that each carry a time-varying current to produce an electromagnetic field. The furniture also includes a controller that selectively provides current to one or more of the primary coils based on their position with respect to the secondary coil.

Further features and advantages of the present invention as well as the structure and operation of various embodiments of the present invention are described in detail below with reference to the accompanying drawings. In the drawings, like reference numerals indicate identical or functionally similar elements. Additionally, the left-most one or two digits of a reference numeral identifies the drawing. in which the reference numeral first appears.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and further advantages of the invention will be more clearly appreciated from the following detailed description when taken in conjunction with the accompanying drawings. In the drawings like reference numerals indicate like structures or method steps, in which the left-most one or two digits of a reference numeral indicates the number of the figure in which the referenced element first appears (for example, the element **210** appears first in FIG. **2**, the element **1010** first appears in FIG. **10**). In the figures:

FIG. **1** is a schematic and functional block diagram of an electromagnetic field source in accordance with one embodiment of the present invention;

FIG. **2** is a schematic cross-sectional top view of a secondary coil and associated components, including an artificial heart, implanted in a recipient reclining on a mattress having embedded therein the electronic field source of FIG. **1**;

FIG. **3** is a functional block diagram of one embodiment of a current director of one embodiment of a controller of the electromagnetic field source of FIG. **1**;

FIG. **4**A is a schematic top view of four primary coils arranged in a generally square-shape pattern and having the same direction of current flow, such as may be employed in an exemplary embodiment of the electromagnetic field source of FIG. **1**;

FIG. **4**B is a schematic top view of one embodiment of a primary coil that generates a magnetic field generally equivalent to the magnetic fields generated by the primary coils of FIG. **4**A;

FIG. **4**C is a schematic top view of eight primary coils arranged in two adjacent square-shape patterns, the coils of one pattern having opposite directions of current flow from the coils of the other pattern, such as may be employed in an exemplary embodiment of the electromagnetic field source of FIG. **1**;

FIG. **4**D is a schematic top view of one embodiment of two adjacent primary coils that generate a combined magnetic field generally equivalent to the magnetic fields generated by the primary coils of FIG. **4**C;

FIG. **5**A is a schematic top plan view of a single primary coil such as may be employed in an exemplary embodiment of the electromagnetic field source of FIG. **1**;

FIG. **5**B is a schematic cross-sectional side view of the primary coil of FIG. **5**A, showing magnetic fields produced by the primary coil;

FIG. **6**A is a schematic top plan view of two adjacent primary coils, having current flows in the same direction, such as may be employed in an exemplary embodiment of the electromagnetic field source of FIG. **1**;

FIG. **6**B is a schematic cross-sectional side view of the primary coils of FIG. **6**A, showing magnetic fields produced by the primary coils;

FIG. **7**A is a schematic top plan view of two adjacent primary coils, having current flows in opposite directions, such as may be employed in an exemplary embodiment of the electromagnetic field source of FIG. **1**;

FIG. **7**B is a schematic cross-sectional side view of the primary coils of FIG. **7**A, showing magnetic fields produced by the primary coils;

FIG. **8**A is a schematic cross-sectional top view of two horizontally disposed primary coils in the same plane such as may be employed in an exemplary embodiment of the electromagnetic field source of FIG. **1**, including a mattress in which the coils are embedded;

FIG. **8**B is a schematic cross-sectional side view of the primary coils and mattress of FIG. **8**A;

FIG. **8**C is a schematic cross-sectional side view of two primary coils disposed at opposing acute angles to the horizontal, such as may be employed in an exemplary embodiment of the electromagnetic field source of FIG. **1**, including a mattress in which the coils are embedded;

FIG. **8**D is a schematic cross-sectional side view of one horizontally disposed primary coil and two vertically disposed primary coils at opposing ends of the horizontal coil, such as may be employed in an exemplary embodiment of the electromagnetic field source of FIG. **1**, including a mattress in which the coils are embedded;

FIG. **9**A is a schematic cross-sectional top view of three horizontally disposed primary coils, two of which are in the same plane and the third of which is in a parallel plane, such as may be employed in an exemplary embodiment of the electromagnetic field source of FIG. **1**, including a mattress in which the coils are embedded;

FIG. **9**B is a schematic cross-sectional side view of the primary coils and mattress of FIG. **9**A; and

FIG. **10** is a schematic cross-sectional top view of a two-plane, interlaced, array of horizontally disposed pri-

mary coils such as may be employed in an exemplary embodiment of the electromagnetic field source of FIG. **1**, including a mattress in which the coils are embedded.

DETAILED DESCRIPTION

I. Introduction

The attributes of the present invention and its underlying method and architecture will now be described in greater detail in reference to one embodiment of the invention, referred to as an electromagnetic field source (EFS) **100**, aspects of which are represented in FIGS. **1** through **10**. In this detailed description, references are made to various functional modules of the present invention that may be implemented using software, hardware including electronic circuits, firmware, or any combination thereof. Some of these implementations may also include a microprocessor (not shown) to execute the software or firmware in accordance with techniques well known to those skilled in the relevant arts. Such a microprocessor may be one of a variety of known types, or a microprocessor to be developed in the future.

FIG. **1** is a schematic and functional block diagram of EFS **100** suitable for implementation in a transcutaneous energy transfer (TET) system. EFS **100** primarily includes primary coils **110**A and **110**B (collectively and generally referred to as primary coils **110**) and a controller **120**. As shown in FIG. **1** EFS **100** is connected to TET primary circuits **140** and a power supply **130**. Primary. coils **110** generate electromagnetic fields for providing energy to a secondary coil that, in this exemplary embodiment, is implanted in a human recipient. Controller **120** selectively provides current to one or more of primary coils **110** based on a number of factors such as the relative position and orientation of the primary and secondary coils, the configuration of the coils, the power to be transferred, the magnitude of the current, among others. Such factors are determined by the application of the invention and the manner in which the invention is implemented, as described in detail below.

A particular implementation of EFS **100** for use as part of a transcutaneous energy transfer (TET) device for powering an artificial heart is shown in FIG. **2**. FIG. **2** is a schematic drawing of EFS **100** embedded in a mattress **210**. Also schematically shown is a human implant recipient **205** reclining on mattress **210**. The implanted components include a total artificial heart **215**, an internal battery **220**, a secondary coil **230**, internal electronics **240**, and connecting wires **250**. Embedded in the mattress are primary coils **110**A and **110**B (shown in an alternative, oval, configuration), controller **120**, TET primary circuits **140**, and power supply **130**.

II. Primary Coils

As shown in FIG. **1**, EFS **100** includes an exemplary configuration of two primary coils, primary coils **110**A and **110**B. It will be understood that many other configurations are possible in accordance with the present invention. Specifically, any number of primary coils may be included in other configurations. The primary coils are not limited to the square shape of coils **110** shown in FIG. **1** or the oval shape shown in FIG. **2**. Coils **110** may be any shape in two or three dimensions, and the coils may be arranged in any pattern rather than be limited to the row pattern shown. The direction of current flow may be in the clockwise (CW) direction, rather than in the counter-clockwise (CCW) direction shown with respect to coils **110**. Also, any number of loops may be included in each coil, for ease of illustration, one winding or loop is shown in the illustrative examples of coils **110**.

As is well known to those skilled in the relevant art, the magnetic field (B) that is generated by a coil having "N" loops and a characteristic radius of "r" is given by equation

$$B = \frac{\mu_o N i}{2r}, \tag{1}$$

in which μ_o is the permeability constant for free space (equal to 4π times 10^{-7} weber per ampere·meter), i is the current through the primary coil in amperes, r is expressed in meters, and B is therefore expressed in weber per square meter.

As also is well known, the magnetic field generated by a larger coil may be generated by a magnetically equivalent configuration of smaller coils. FIGS. **4**A–**4**D provide illustrative examples. In FIG. **4**A, currents in coils **410**A–D (collectively referred to as coils **410**) are shown as flowing in a clockwise direction. The coils **410** are roughly square shape, and are positioned at the corners of a square pattern. It will be understood that these current flows show an instantaneous or steady state direction, and that the direction may be reversed. It is assumed for illustrative purposes that, when a current flow is reversed, it is reversed for all energized primary coils in the same manner. Thus, for example, a comparison between two adjoining primary coils in which currents flow in opposite directions generally is applicable both to steady state and alternating current conditions. For clarity and convenience, references hereafter to the direction of current flow will be made with respect to an instantaneous or steady state direction. Alternatively, the direction of current flow may be considered to be the sense of direction of the winding of the coil.

As will be evident to those skilled in the relevant art, some components of the magnetic fields of coils **410** tend to cancel each other out. Specifically, those components generated by currents flowing in opposite directions, such as the loop-segment pairs **411** and **412**, or **413** and **414**, i.e., those in the interior of the square pattern, produce generally opposing magnetic fields. In contrast, magnetic fields generated by the loop-segments on the exterior of the square pattern, such as segments **415** and **416**, are not opposed by magnetic fields generated by other loop segments in the pattern. Thus, the combination of magnetic fields generated by primary coils **410** is generally equivalent to the magnetic field generated by primary coil **420** of FIG. **4**B.

Similarly, the combined magnetic field generated by primary coils **430**A–H has a shape that is generally equivalent to the combined magnetic fields of primary coils **440**. Specifically, the square pattern of coils **430**A–D, having current flowing in a clockwise direction, produces a magnetic field generally equivalent to that produced by coil **440**A, which also has clockwise current flow. The square pattern of coils **430**E–H, having a counter-clockwise current flow, produces a magnetic field generally equivalent to that produced by coil **440**B. Thus, the configuration of FIG. **4**C is generally equivalent to that of FIG. **4**D in terms of the magnetic fields produced by the coils of those figures.

FIGS. **5**A and **5**B provide greater detail with respect to the magnetic fields produced by a single primary coil such as coil **420** of FIG. **4**B. FIG. **5**A is a schematic top plan view of a single primary coil, coil **510**, disposed in a plane **520**. It will be assumed for illustrative purposes that plane **520** is horizontal. For example, it may be a plane in a horizontally disposed mattress, such as mattress **210**. Current flows through coil **510** in a counter-clockwise direction. FIG. **5**B is a cross-sectional side view along cross-section line **5**B—**5**B through loop segments **511** and **512**. The notations "O" and "X" in the cross section of plane **520** respectively represent current flow out of and into the drawing page through loop segments **511** and **512**. Iso-magnetic contours

551 and 552 respectively represent the magnetic fields generated by current flowing through loop segments 511 and 512 in the described directions. The direction and magnitude of the magnetic fields are schematically represented by arrows 561–568. For illustrative purposes, relatively weak magnetic fields are represented by small arrows, and large arrows are used to represent stronger magnetic fields. It should be appreciated that such diagrammatic representations are representational only and are not intended to be precise with respect to their size, shape or orientation.

Also shown in FIG. 5B, but omitted from FIG. 5A for clarity, is a second horizontal plane 530 disposed above plane 520. It is assumed for illustrative purposes that a secondary coil 230 implanted in recipient 205 is disposed within plane 530 at a position represented in phantom outline by slot 540A. As shown, position 540A is located so that its projection on plane 520 is generally within the interior of coil 510.

Components of the magnetic fields generated by loop segments 511 and 512 generally reinforce each other in certain areas, such as the interior area of coil 510. These reinforced magnetic field components are represented by large arrows 564 and 565 that are directed upward from plane 520 toward plane 530. More specifically, magnetic fields represented by exemplary iso-magnetic contour lines 551 and 552 are oriented in the same direction (upward toward plane 530), and thus are reinforcing, in the regions of arrows 564 and 565. Elsewhere, such as in the regions of small arrows 561 and 566, there is no such reinforcement.

If secondary coil 230 is in position 540A, i.e., in a plane parallel to that of primary coil 510 and generally vertically aligned with the interior of coil 510, then, as is well known by those skilled in the relevant art, primary coil 510 induces a current to flow in secondary coil 230. The magnetic field that induces this current flow is represented by arrows 564 and 565. In contrast, if secondary coil 230 is disposed in plane 530 at a position generally outside of the interior of coil 510, such as positions 540B or 540C, then primary coil 510 generally does not induce a current to flow in secondary coil 230.

More specifically, the magnetic fields acting on secondary coil 230 when in position 540B or 540C generally are in the same or parallel plane as the coils, and thus, as is well known, induce weak or no current with the coils. In addition, even if secondary coil 230 were perpendicular to the direction of the magnetic field, those fields outside the perimeter of the primary coil (such as are represented by arrows 561 or 566) generally are weaker than those in the interior (such as represented by arrow 564). For convenience, such areas in the magnetic fields; i.e., those that induce weak or no currents in secondary coils located in those areas, are referred to hereafter as "dead zones."

FIGS. 6A and 6B provide greater detail with respect to the magnetic fields produced by two primary coils in proximity to each other, such as coils 110 shown in FIG. 1. FIG. 6A is a schematic top plan view of primary coils 610A and 610B (coils 610), disposed in a horizontal plane 620. Current flows through both of coils 610 in the same direction, i.e., counter-clockwise in this example. FIG. 6B is a cross-sectional side view of coils 610 in FIG. 6A taken along cross-section line 6B—6B. Iso-magnetic contours 651–654 respectively represent the magnetic fields generated by current flowing through loop segments 611–614 in the indicated directions.

As noted, the magnetic fields in the interior of the coils tend to reinforce, and thus produce combined magnetic fields such as are represented by large arrows 661 and 662 (with respect to coil 610A) and 663 and 664 (with respect to coil 610B). Also, between coils 610A and 610B the magnetic fields generated by loop segments 612 and 613 tend to reinforce each other in the upward direction, as represented by large arrow 665.

A second horizontal plane 630 is shown above plane 620 in FIG. 6B, but is omitted from FIG. 6A for clarity. As with respect to FIG. 5B, it is assumed for illustrative purposes in FIG. 6B that secondary coil 230 may be positioned in various locations in plane 630, as indicated by representative regions 640A–640C shown in phantom outline. A horizontally-disposed secondary coil 230 is activated when located in any region 640 due to then orthogonal intersection with the vertically-oriented magnetic fields generated by primary coils. The word "activated" means in this context that one or more primary coils have produced a magnetic field of any strength, and in an orientation, sufficient to induce an operative current in secondary coil 230. The word "operative" means that the current is sufficient to enable secondary coil 230 to perform its function, such as powering circuits related to artificial heart 215 or recharging internal battery 220.

Another case is now considered in which current is flowing in opposite directions through two adjacent primary coils. FIG. 7A is a schematic top plan view of primary coils 710A and 710B (coils 710), disposed in a horizontal plane 720. Current flows through coil 710A in a counter-clockwise direction, and current flows through coil 710B in a clockwise direction. FIG. 7B is a cross-sectional side view taken along cross-section line 7B—7B through loop segments 711 and 712 of coil 710A and loop segments 713 and 714 of coil 710B. Current flows out of the drawing page through loop segments 711 and 714, and into the drawing page through loop segments 712 and 713. Iso-magnetic contours 751 and 753 respectively represent the magnetic fields generated by current flowing through loop segments 711 and 714. Iso-magnetic contour 752 represents the combined magnetic field generated by current flowing through loop segments 712 and 713.

Large arrows 761 and 762 represent the relatively strong magnetic fields generated in a vertical direction in the interior of primary coil 710A due to reinforcement, as described above. Similarly, large arrows 763 and 764 represent the relatively strong magnetic fields generated in a vertical direction in the interior of primary coil 710B. In contrast, in accordance with effects well known by those skilled in the relevant art, the magnetic fields generated by loop segments 712 and 713 tend to generate a relatively strong magnetic field in a horizontal direction. This horizontal magnetic field between coils 710A and 710B is represented by large arrows 765 and 766. Also, non-reinforced magnetic fields are generated in a generally horizontal orientation by loop segments 711 and 714, as indicated by small arrows 767 and 768.

A representative series of five vertical positional slots 730A–E (positions 730) are shown above plane 710 in FIG. 7B, but are omitted from FIG. 7A for clarity. It is assumed for illustrative purposes that secondary coil 230 may be positioned in any position 730 or therebetween. If secondary coil 230 is positioned in positions 730B or 730D, i.e., vertically oriented approximately over the middle of coils 710A and 710B, respectively, coil 230 generally will not be activated. Lack of activation is due to the fact that the vertical orientation of secondary coil 230 coincides with the vertical orientations of the magnetic fields (arrows 761 and 763) in these locations. If secondary coil 230 is positioned in position 730C approximately between coils 710A and

710B, it generally is activated because the vertical orientation of secondary coil **230** is perpendicular to the horizontal orientation of the magnetic field (arrow **765**) at this location.

Similarly, secondary coil **230** generally is activated if it is positioned in positions **730**A or **730**E, that is, approximately over the exterior loop segments **711** and **714** of coils **710**A and **710**B, respectively. The word "exterior" is used in this context to refer to loop segments of an energized primary coil located generally opposite to loop segments of the same coil that are close to loop segments of another energized primary coil. Activation is attained because the vertical orientation of secondary coil **230** is perpendicular to the horizontal magnetic field.

However, because the magnetic fields represented by arrows **767** and **768** are not reinforced, it may be necessary to increase the strength of these fields in order to sufficiently activate secondary coil **230** to meet desired performance standards. As indicated by equation number one, one way to increase the magnetic fields represented by arrows **767** or **768** is to increase the current through primary coils **710**A or **710**B, respectively. For example, if coils **710** are located at the edge, then the currents may be increased. Also, the number of loops in the primary coils may be increased based on a determination of the strength that these weaker magnetic fields must exhibit in order to activate secondary coil **230**.

Aspects of the operation and arrangement of primary coils of EFS **100** are now further described with respect to an illustrative example. It is assumed in this example that recipient **205** may move to any position on mattress **210**, and assume any orientation between horizontal (i.e. lying on the back or stomach) and vertical (i.e., lying on a side). Also, recipient **205** may be positioned immediately above mattress **210**, or at a greater distance from it, as when lying on pillows or sitting in bed. Thus, secondary coil **230** may be aligned above any portion of mattress **210**, may be located either on or at a distance from mattress **210**, and may be disposed in any orientation with respect to the plane of mattress **210**.

In accordance with one embodiment, a small number of relatively large primary coils, such as coils **110**A and **110**B as shown in FIG. **2**, may be used. FIGS. **8**A–**8**D show three illustrative configurations employing a small number of large primary coils in a horizontally disposed mattress **800**.

FIG. **8**A is a schematic cross-sectional top view of mattress **800** including primary coils **810**A and **810**B (coils **810**). FIG. **8**B is a cross-sectional side view of the configuration of FIG. **8**A along cross-section line **8**B—**8**B. The configuration of FIGS. **8**A and **8**B is similar to that of FIG. **1** with respect to the location of primary coils **110**. As shown in FIG. **8**B, coils **810** are disposed approximately in the same plane.

It may first be assumed that secondary coil **230** is positioned above either primary coil **810**A or **810**B (i.e., so that the vertical projection of secondary coil **230** falls approximately within one of coils **810**). It is also assumed that secondary coil **230** is horizontally disposed; i.e., it is in approximately the same plane as primary coils **810**. In this case, secondary coil **230** may be activated by providing current, in either direction, to whichever of coils **810** secondary coil **230** is above. This primary coil is referred to for convenience as the "closest" primary coil, meaning that it is the "closest" of the primary coils to the secondary coil. Hereafter, "closest" similarly will be used to mean the primary coil, or group of primary coils, that are closer to the secondary coil than any other primary coils.

The closeness, or proximity, of coils to each other may be defined and determined in different ways, depending, for example, on the type of proximity sensor that is used. Thus, for a resonance frequency shift sensor, such as is described below with respect to the operations of proximity detector **126**, closeness generally relates to magnetic proximity in the sense that coils are closest if their mutual inductance is strongest. If other kinds of sensors are used, such as optical or mechanical sensors, closeness generally relates to the physical proximity of the coils.

It is now assumed for illustrative purposes that secondary coil **230** is positioned above and approximately between coils **810**. In this case, secondary coil **230** may be activated by applying currents to coils **810**A and **810**B in the same direction. The magnetic fields generated by coils **810** thus generally are as shown in FIG. **6**B with respect to coils **610**. That is, a strong, vertically oriented, magnetic field (such as shown by arrow **665** of FIG. **6**) perpendicularly intersects horizontally positioned secondary coil **230**.

Secondary coil **230** is now assumed to be disposed in a vertical orientation and located approximately between primary coils **810**. In this case, secondary coil **230** may be activated by applying currents to coils **810**A and **810**B in opposite directions. The magnetic fields generated by coils **810** thus generally are as shown in FIG. **7**B with respect to coils **710**. That is, a strong, horizontally oriented, magnetic field (such as shown by arrow **765** of FIG. **7**) perpendicularly intersects vertically positioned secondary coil **230**. Similarly, if secondary coil **230** is positioned generally above an exterior loop segment of coils **810**, such as loop segments **801** or **802**, it will be intersected by a magnetic field perpendicular to it, although this field generally will be weaker than the one between the coils. However, as noted above with respect to similar fields **767** and **768** of FIG. **7**, secondary coil **230** may be activated by increasing the current through the closest coil so that the magnetic field is increased in strength, or by varying other parameters such as the number of loops in the primary coils.

Finally, the case is considered in which secondary coil **230** is disposed in a vertical orientation and located approximately above the middle of one of primary coils **810**. In this case, it generally is not possible to activate secondary coil **230** because it is in approximately the same plane as the magnetic field generated by the closest primary coil. This situation is shown in FIGS. **6**B and **7**B with respect to vertically oriented magnetic field arrows **661**, **663**, **761**, and **763**. Thus, the configuration of FIG. **8**B; i.e., in which the primary coils are in the same horizontal plane, generally is not appropriate if secondary coil **230** may be in a predominantly vertical orientation and it is required that it may be activated at every location over horizontal mattress **800**.

However, the configuration of FIG. **8**B may nonetheless be employed in a variety of circumstances. For example, secondary coil **230** may be constrained to remain predominantly in a horizontal position, i.e., in a plane predominantly parallel to the plane of the primary coils. Alternatively, more than one secondary coil may be used; for example, two secondary coils that are perpendicularly oriented with respect to each other may be employed.

To illustrate a more general case, it is now assumed that the primary coils of EFS **100** must be positioned so that one or more of them may activate a single secondary coil **230** irrespective of the location or orientation of recipient **205** with respect to mattress **210**. For convenience, this illustrative condition is referred to as a requirement for "full coverage." It will be understood that, in alternative embodiments, full coverage need not be required. For example, in some applications it may be provided that a secondary coil need not be activated if it is located at certain

positions on or over the housing of the primary coils, or, as just noted, is disposed in particular orientations.

FIGS. **8**C, **8**D, **9**A, and **9**B show illustrative configurations that may be used to achieve full coverage. It will be understood that many alternative configurations are possible. In FIGS. **8**C, **8**D, **9**A, and **9**B, in contrast with the configuration of FIGS. **8**A and **8**B, the primary coils of EFS **100** are not disposed in the same plane. FIG. **8**C is an illustrative example of two primary coils **820**A and **820**B (coils **820**) that are similar to primary coils **810** except that they are disposed on separate, intersecting, planes. In particular, coil **820**A forms an acute angle from near the center of the bottom surface **806** of mattress **800** upwards towards side **801** and top surface **805** of mattress **800**. Primary coil **820**B similarly forms an acute angle from near the center of the bottom surface **806** upwards towards an opposite side **802** of mattress **800**. Thus, primary coils **820** form a roughly "V" shape in cross section.

Assuming again for convenience of reference that mattress **800** is horizontally oriented, both of coils **820** may generate magnetic fields that are perpendicular to their planes and thus have both horizontal and vertical components. Therefore, if secondary coil **230** is vertically disposed at any point above the interiors of either of coils **820**, a horizontal component of the magnetic field of the closest of primary coils **820** may be generated in order to activate secondary coil **230**. As is evident, the amount of current required to activate secondary coil **230** depends, among other things, on the angles of coils **820** with respect to the horizontal, and on the sizes and numbers of loops of the coils. Also because of the presence of both horizontal and vertical components, and for the reasons discussed above with respect to inter-coil magnetic fields as illustrated in FIGS. **6**B, **7**B, and **8**B, a vertically oriented secondary coil **230** also is activated if it is located between coils **820**.

Similarly, because coils **820** generate magnetic fields having vertical components, secondary coil **230** is activated if it is located anywhere over the surface of mattress **800** and oriented horizontally. This case is similar to that of FIG. **8**B except that, other factors being equal, the magnitudes of the vertical magnetic field components of coils **820** generally will be less than those of coils **810** because of the angular orientations of coils **820** with respect to the horizontal.

FIG. **8**D illustrates an alternative configuration in which horizontal primary coil **830**A is positioned between two vertical primary coils **830**B and **830**C. In this exemplary configuration, coil **830**A is embedded in mattress **800** whereas coils **830**B and **830**C adjoin opposing sides **801** and **802** of mattress **800**, respectively. Coils **830**B and **830**B may be contained within side boards of a bed including mattress **800**, for example. Primary coil **830**A thus is capable of generating vertically oriented magnetic fields, and primary coils **830**B and **830**C are capable of generating horizontally oriented magnetic fields, across all of top surface **805**. Secondary coil **230** thus may be activated irrespective of its position or orientation above mattress **800**, provided that it is not too far removed from mattress **800**. As is evident, the operational range of secondary coil **230** above top surface **805** depends on the strength of the magnetic fields generated by primary coils **830** and by the height above top surface **805** of primary coils **830**B and **830**C.

It will be understood, based on the description above with respect to FIGS. **4**A–**4**D, that any of the primary coils represented in FIGS. **8**A–**8**D may be replaced with magnetically equivalent groups of smaller primary coils. For example, primary coil **830**A may have a perimeter that is approximately co-extensive with the perimeter of top surface **805** of mattress **800**. It may be replaced with a functionally equivalent array of smaller primary coils arranged so that the exterior loop segments of the array also are generally co-extensive with the perimeter of top surface **805**. Thus, in one of many possible configurations, primary coil **830**A may have a shape similar to that of primary coil **420** of FIG. **4**B, and it may be functionally replaced with an array of four smaller or eight even smaller primary coils arranged and configured as shown in FIG. **4**A with respect to primary coils **410**.

Yet another type of configuration that may be used to achieve full coverage is shown illustratively in FIGS. **9**A and **9**B. FIG. **9**A is a schematic cross-sectional top view of three horizontally disposed primary coils **910**A–C (coils **910**). FIG. **9**B is a schematic cross-sectional side view of coils **910** along cross-section line **9**A—**9**A. Two of the coils, **910**A and **910**B, are in approximately the same plane, as indicated in FIG. **9**B. The third coil, **910**C, is in a plane that is approximately parallel to, and below (or, in an alternative implementation, above), the plane of coils **910**A and **910**B. As seen from the top-view perspective of FIG. **9**A, an overlap area **921** is defined by the vertical projection of coil **910**C on coil **910**A, and a similar overlap area **922** is defined by the vertical projection of coil **910**C on coil **910**B. Also, an inter-coil area **920** is shown that is between coils **910**A and **910**B, but within the projection of coil **910**C.

As noted with respect to FIG. **6**B, a horizontally disposed secondary coil **230** positioned between two first primary coils in the same plane may be activated by energizing both first primary coils using current flowing in the same direction. Alternatively, such a disposed secondary coil may be activated by energizing another primary coil that is positioned between the first primary coils in another plane. For example, if secondary coil **230** is located in inter-coil area **920** between coils **910**A and **910**B, it may be activated either by energizing coils **910**A and **910**B with current flowing in the same direction, or by energizing coil **910**C. Because secondary coil **230** is, in this example, positioned above the interior of coil **910**C, it will be activated by a vertical magnetic field generated by coil **910**C above its interior.

Importantly, the configuration of FIGS. **9**A and **9**B may also be used to achieve full coverage with respect to secondary coil **230** in a vertical orientation. As noted, a vertically disposed secondary coil **230** generally positioned between two primary coils, or above exterior loop segments, may be activated by energizing both primary coils using current flowing in opposite directions. However, as also noted, vertically oriented secondary coil **230** positioned above the middle of a primary coil generally may not be activated by that coil. Nonetheless, such a positioned and oriented secondary coil may be activated by a primary coil generally positioned so that one of its exterior loop segments is aligned with the middle of the other primary coil. For example, primary coil **910**C, having exterior loop segments **911** and **912**, may activate secondary coil **230** if it is vertically oriented and positioned in positions **930**B or **930**C, respectively. These positions are generally aligned with exterior loop segments **911** and **912**, and thus a weaker, horizontally oriented, magnetic field is produced through those positions in the manner shown by arrows **767** and **768**. As is evident, the magnitude of this magnetic field generally decreases with distance from the energized loop segment; thus, the magnetic field at regions/positions **930**A or **930**D generally will be weaker than those at **930**B or **930**C. In addition to the previously noted steps of increasing current or number of loops, this potential deficiency in fill coverage may be avoided by providing interlaced arrays of primary coils in two or more planes.

FIG. **10** illustrates one example of interlaced arrays of primary coils. In addition to addressing potential deficiencies in full coverage, such arrays may have an additional benefit of reducing the amount of power required by EFS **100**. That is, less power generally is required to activate a secondary coil by generating a magnetic field from a small primary coil close to the secondary coil than from a more distant primary coil or from a large primary coil covering a large area. Arrays of smaller primary coils provide that one or more of the primary coils will be close to the secondary coil, and thus less power generally will be required than if more distant, or larger, primary coils were employed. In some applications, a similar benefit is derived from the fact that the magnetic field generated by a small primary coil of an array is more localized than the magnetic field generated by a large primary coil. For example, the generation of large-area magnetic fields may interfere with medical equipment, or adversely interact with metallic objects in or around the recipient.

It will be understood that although the configurations of FIGS. **9**A, **9**B, and **10** are described herein for convenience as having primary coils disposed in two planes (which may include additional planes in alternative configurations), the coils in those planes may, in practice, be very close together. They may be so close as to essentially provide a single plane with interwoven primary coils. For example, FIG. **10** is a schematic cross-sectional top view that shows what is referred to as two parallel planes of primary coils. A first plane, shown in solid lines, includes representative coils **1010**A–D of an array of first-plane primary to coils **1010**. A second plane, referred to as including an array of second-plane primary coils, is shown in phantom outline. Coils **1020**A–D are representative of this array of second-plane primary coils **1020**. In one of many possible implementations, coils **1010** and **1020** may consist of wires woven into, or positioned within, a blanket such that the loop segments of coils **1010** cross under, and may touch (if electrically insulated), loop segments of coils **1020** where they cross. For clarity and convenience of illustration, coils **1010** and **1020** are schematically represented by squares that are disposed within a horizontally oriented mattress **1000**. Lead wires into and out of the coils are not shown for clarity.

As is evident from FIG. **10** and the preceding description relating to FIGS. **9**A and **9**B, coils **1010** and **1020** provide full coverage over the surface of mattress **1000**. (As also is evident, coverage at the perimeter of mattress **1000** may be achieved by the placement of primary coils adjacent to this perimeter, which are also omitted in FIG. **10** for clarity.) Full coverage using two planes of primary coils has already been described with respect to FIGS. **9**A and **9**B. In that description, however, it was noted that a vertically oriented secondary coil **230** positioned as in positions **930**A or **930**D, ie., at some distance from the external loop segment of the closest primary coil, may not be activated unless current is increased, or another measure is taken, to increase the magnetic field generated by that external loop segment. The arrays of primary coils **1010** and **1020** provide an alternative way of providing that secondary coil **230**, in such orientation and position, will be activated.

For example, it is assumed that secondary coil **230** is vertically oriented and positioned in the middle of first-plane primary coil **1010**D, as schematically represented in FIG. **10**. Secondary coil **230** may be activated by energizing any one, or any combination, of second-plane primary coils **1020**A–D. Similarly, if secondary coil **230** is vertically oriented and positioned approximately in the middle of second-plane primary coil **1020**A, it may be activated by energizing any one, or any combination, of first-plane primary coils **1010**A–D. It should be understood that primary coils **1010**A–D may be at other orientations, such as at a 45° orientation. As is evident from FIG. **10**, the size of primary coils **1010** and **1020** generally may be determined by the size of secondary coil **230**, among other factors.

Alternative, but not exhaustive, ways of providing full coverage have now been described. These alternatives depend on various configurations of primary coils, the selection of one or more primary coils closest to the secondary coil, the orientation of the secondary coil with respect to the plane or planes of the primary coils, and the strength of the magnetic fields based on various factors such as current strength and the direction of the magnetic field by proper choice of current directions through the coils. Now to be described are the operations of EFS **100** with respect to determining which of the primary coils are closest, the orientation of the secondary coil, and the amount of current to provide to the closest primary coils.

III. Controller

As noted, controller **120** selectively provides current to one or more primary coils based on their proximity, and/or orientation with respect, to the secondary coil. For convenience, controller **120** is hereafter equivalently described as selectively providing current to one or more primary coils based on their "position" with respect to the secondary coil. As shown in FIG. **1**, controller **120** includes current director **124**, proximity detector **126**, and orientation detector **122**, the operations of which are now described.

A. Current Director

Current director **124** selectively directs time-varying currents through the closest primary coils. Current director **124** operates in cooperation with TET primary circuits **140** and power supply **130**. Specifically, TET primary circuits **140**, powered by power supply **130**, fashion alternating currents suitable for energizing primary coils in a TET. TET primary circuits **140** may include any of a variety of known circuits for performing such a function, or may include circuits to be developed in the future. The functions of current director **124** are shown in greater detail in FIG. **3**.

1. Power Adjuster

Current director **124** includes power adjuster **310** that adjusts the amount of current directed to the closest primary coils based on a number of factors. Any of a variety of known techniques may be used to effectuate such adjustment; for example, any known amplifier circuit may be employed.

One factor in determining the amount of adjustment is the proximity of the secondary coil to the closest primary coils. In one exemplary embodiment, a default value for the amount of current may be assumed by power adjuster **310**. This default value may, for example, be a minimum value that will activate secondary coil **230** if it is located at a distance from the plane of the primary coils within an average range. This value may be determined empirically, by computation, or by a combination thereof. It is assumed for illustrative purposes that the anterior-posterior dimension of an average person ranges from nine to twelve inches in the area of the abdomen where a secondary coil may be implanted for operating a total artificial heart. If the primary coils are implanted two inches below the top surface of a mattress on which the recipient reclines, the default value may be such that secondary coil **230** will be activated if it is located 14 inches from the closest primary coils. If proximity detector **126** detects that secondary coil **230** may be further from the closest primary coils than 14 inches in this illustrative example, power adjuster **310** may increase the

amount of current so that the magnetic fields generated by the closest primary coils nonetheless will be sufficient to activate secondary coil **230**.

The amount of current required to activate secondary coil **230** also depends, as noted, on the size, shape, and number of loops of the closest primary coils. In the illustrated embodiment, the number of loops in each primary coil is predetermined in accordance with calculations based on equation number one, above, using an assumed size of secondary coil **230**. As will be evident to those skilled in the relevant art, many other known equations and techniques may be used to determine a default, or other, current value.

To provide one example with respect to the illustrated embodiment, it is assumed that secondary coil **230** is circular with a diameter of three inches. It may be determined empirically, in view of the requirements of a typical total artificial heart **215** and battery **220**, that the required magnetic field for effective coupling to this secondary coil **230** is approximately $10^{31\ 4}$ weber/meter^2. To generate 10^{-4} weber/meter^2, a combination of N=3 turns, i=4 amperes, and r=0.05 meter (4" diameter) is adequate in typical circumstances in which secondary coil **230** is closely coupled to the closest primary coil. Assuming that secondary coil **230** may be on the order of 12 inches away from secondary coil **230**, the number of primary turns may be increased to maintain the same field strength without an increase in the current used. A combination of N=9 turns, i=4 amperes, and r=0.15 meter (12" diameter or square edge) is typically adequate to activate secondary coil **230** under these assumed circumstances. It will be understood that these calculations are illustrative only, and that many other solutions are possible under alternative assumptions.

As noted, the orientation of secondary coil **230** may indicate that the current to the closest primary coils should be increased (or, alternatively, that the number of loops in each primary coil be increased to take orientation into account). For example, if secondary coil **230** is determined to be predominantly perpendicular to the plane or planes of the primary coils, and located above an external loop segment of the closest primary coil (e.g. position **730**A of FIG. **7**) rather than between closest primary coils (e.g. position **730**C), then power adjuster **310** may increase current in order to increase the strength of the magnetic field generated by the closest primary coil.

Further, as noted, a typical distance from implanted secondary coil **230** to the surface of a mattress may be greater for a recipient lying on his or her side than if the recipient were in lying on his or her stomach or back. Also, the recipient may not be lying directly on the mattress, but may be reclining on pillows, sitting up, or be otherwise disposed away from the mattress. In the illustrated embodiment, proximity detector **126** detects such greater-than-normal distance, and power adjuster **310** therefore increases the amount of current. In other embodiments, a worst-case situation may be assumed such that it is not necessary to adjust the amount of current to the closest primary coils. That is, the default value is great enough to ensure that secondary coil **230** will be activated within any foreseeable range of distances from the primary coils. In such embodiments, power adjuster **310** need not be included.

2. Current Direction Determiner

Current director **124** also includes current direction determiner **320** that determines the directions of current supplied to two or more closest primary coils. In some instances, there may be only one closest primary coil, in which case current direction. determiner **320** need not be employed. For example, secondary coil **230** may be positioned above the middle of a primary coil and oriented in the same plane as that coil (e.g., it is positioned in position **640**B of FIG. **6**). Thus, only that primary coil need be energized and direction of current flow is immaterial with respect to alternating current through a single coil. In other instances, however, it may be required to energize two or more primary coils.

For example, secondary coil **230** may be positioned between two closest primary coils in approximately the same plane as those coils (e.g., it is positioned in position **640**A of FIG. **6**). To activate secondary coil **230** in this position, the two closest primary coils are energized, with current flowing in the same direction (in phase). In another illustrative example, secondary coil **230** may be approximately above the middle of the square pattern made by primary coils **410** of FIG. **4**A; that is, at location **418** between these four coils. If all four of coils **410** are energized by current flowing in the same direction, then, as noted, coils **410** are magnetically approximately equivalent to coil **420** of FIG. **4**B. Thus, secondary coil **230** is activated by the energizing of coils **410** because such energizing is the approximate equivalent of energizing a coil having a center below, and in the same plane as, the secondary coil.

Current direction determiner **320** thus analyzes information from proximity detector **126** and orientation detector **122** to determine the relative directions of current flow in the two or more closest primary coils. Such analysis may be carried out in accordance with any of a variety of known techniques. For example, firmware including analog-to-digital converters and logical elements may be employed; appropriate software may be executed by a microprocessor (not shown); analog electrical comparator circuits may be employed, and so on.

3. Primary Coil Selector

Also included in current director **124** is primary coil selector **330** that selects primary coils to receive current. In the illustrated embodiment, this selection is made based on information provided by proximity detector **126** and orientation detector **122**, as described below. Specifically, one or more primary coils are selected based on the detected location and orientation of secondary coil **230** and in accordance with the characteristics of magnetic fields described above. Typically, such selection is made in cooperation with the determinations made by current direction determiner **320**, and in accordance with known techniques as noted with respect to current direction determiner **320**.

Primary coil selector **330** also typically employs any of a variety of known switching techniques and devices to direct current to the selected primary coils. For example, any of a large number of solid-state electronic switches, or mechanical switches, may be employed. In FIG. **3**, this switching function is represented by the connection of primary coil selector **330** to connectors **102–108**. As shown in FIG. **1**, connectors **102** and **104** are respectively connected to the output and input terminals of primary coil **110**A, and connectors **106** and **108** are similarly connected to primary coil **110**B.

B. Proximity Detector

As noted, proximity detector **126** determines the one or more closest primary coils to secondary coil **230**, and may also determine the location of secondary coil **230** with respect to the closest primary coils (ie., between two coils, over the middle of one coil, over an external segment of one coil, and so on). For clarity and convenience, such information hereafter is simply referred to as the "proximity" or "closeness" of secondary coil **230**. As is evident, the proximity of secondary coil **230** to various primary coils typi-

cally changes over time as recipient **205** moves. Thus, the identification of the closest primary coils may consequently change over time. It will thus be understood that the determinations made by proximity detector **126** (and by orientation detector **122**, described below) typically are made at intervals, or they may be made essentially continuously. For example, if calculations and comparisons are made in an analog system, proximity detector **126** may process information continuously. If calculations and comparisons are made in a digital system using firmware, software, or a combination thereof, a period for making calculations may be determined in accordance with any of a variety of known techniques and in accordance with the time needed to execute the firmware or software.

In one embodiment, proximity detector **126** employs well known principles of mutual inductance to determine the proximity of secondary coil **230**. Specifically, the inductances of each primary coil at a selected frequency, referred to as the "primary resonance frequency," are measured. This frequency may, but need not be, different than the frequency at which the alternating current changes direction (the "secondary resonance frequency"). The proximity of the secondary coil results in a mutual inductance that either adds to, or subtracts from, the inductance of the primary coil depending on the winding sense of the secondary compared to the primary. This change in the inductance of the primary coil being measured is referred to herein as a "frequency shift" because it changes the primary resonance frequency. As will be evident to those of ordinary skill in the relevant art, the mutual inductance of closely coupled primary and secondary coils is approximated by the following equation:

$$\frac{M}{L} = \frac{N_2}{N_1}\left(\frac{r_2}{r_1}\right)^2 \quad (2)$$

Where, M is the mutual inductance, L is the inductance of the primary coil without the secondary coil being present, N_2 and N_1 are the number of turns of the secondary and the primary coil, and r_2 and r_1 are the characteristic dimension of the secondary and primary coils, respectively. For typical values, such as provided in the illustrative example provided above with respect to the operation of power adjuster **310**, N_2 equals 18 turns, N_1 equals 9 turns, r_2 equals 1.5 inches, and r_1 equals six inches. Thus, the ratio M/L is approximately equal to 0.125, or about 12 percent. That is, resonance frequency shifts of as much as approximately six percent in each direction, depending on the relative directions of windings, may be expected if secondary coil **230** is proximate to the primary coil being measured.

By thus measuring the proximity of each primary coil, the closest primary coils are determined. Similarly, it may be determined that a particular primary coil is the closest coil, but that the resonance shift is less than would be expected if the secondary coil were positioned at a nominal distance from the middle of the coil. Such reduced shift may be due to the secondary coil being between the measured primary coil and an adjacent primary coil, or at an edge of the measured coil nearer to the adjacent coil. Measurement of the frequency shift of the adjacent primary coil may confirm this.

Otherwise (i.e., if the proximity of the secondary coil to the adjacent primary coil is not as great as would be expected if the secondary coil were between the measured coil and the adjacent coil, or closer to the adjacent coil), the secondary coil may be at a greater-than-nominal distance above the measured primary coil. As will be evident to those skilled in the relevant arts, frequency shift information from the closest and adjacent primary coils may thus be used to determine the proximity and the location of the secondary coil.

Proximity detector **126** in this manner determines the proximity of each primary coil until one or more closest primary coils are identified or, alternatively, the mutual inductance of each primary coil is determined. One reason that it may be advantageous to measure all primary coils, even if it appears that one or more closest primary coils have been detected because of a significant frequency shift, is to avoid an erroneous determination due to the placement of a wire or other magnetically active material on or near mattress **210**. Thus, for example, the distribution of inductance due to an electrical chord placed on the mattress typically will be different than the distribution of inductances due to the proximity of a secondary coil of the type typically implanted in recipient **205**.

If all primary coils are measured and proximity detector **126** does not detect the proximity of secondary coil **230**, then the measurement process may be repeated with more power provided to each primary coil. Optionally, if one or more closest primary coils are not detected, an alarm may be enabled in accordance with known techniques to indicate that the secondary coil is not being activated.

C. Orientation Detector **122**

As previously described, orientation detector **122** determines whether secondary coil **230** is disposed in an orientation predominantly perpendicular, or alternatively, parallel, to the plane or planes of the primary coils. Such orientation is measured in the illustrated embodiment by detecting relative changes in the resonance shifts of adjacent primary coils.

For example, it is assumed that the primary coils are arranged in two parallel layers in accordance with the example of FIG. **10**. It is also assumed that the frequency shift due to mutual inductance, as measured with respect to second-layer coil **1020**A, is relatively high, and that the frequency shift with respect to first-layer coils **1010**A and **1010**B are approximately the same, and are relatively low as compared to that of coil **1020**A. Thus, for the same reasons discussed above with respect to FIGS. **6**B and **7**B regarding the characteristics of magnetic fields, it is determined that secondary coil **230** is predominantly perpendicular with respect to the planes of coils **1010** and **1020**, while being located at the edge of coil **1020**A and equally divided between first-layer coils **1010**A and **1010**B.

As the differences decrease between the frequency shift of coil **1020**A, on the one hand, and coils **1010**A and **1010**B, on the other hand, it may be determined that the predominance of the perpendicular orientation is decreasing; i.e., secondary coil **230** is becoming less perpendicular, and more parallel, to the planes of coils **1010** and **1020**. If the relationship is reversed, such that the frequency shift of coil **1020**A is relatively low in comparison to that of coils **1010**A and **1010**B, then it may be determined that secondary coil **230** is predominantly parallel to the planes of coils **1010** and **1020**. Orientation detector **122** thus determines the orientation of secondary coil **230**, within the range from predominantly perpendicular to predominantly parallel, with respect to the planes of the primary coils.

Having now described one embodiment of the present invention, it should be apparent to those skilled in the relevant art that the foregoing is illustrative only and not limiting, having been presented by way of example only. Many other schemes for distributing functions among the various functional elements of the illustrated embodiment are possible in accordance with the present invention. The

functions of any element may be carried out in various ways in alternative embodiments.

For example, numerous variations are contemplated in accordance with the present invention to carry out the functions of controller **120**. The operations of orientation detector **122**, or portions thereof, may be combined with those of proximity detector **126**, or portions thereof. Similarly, either or both of detectors **122** and **126** may carry out the operations of current director **124**, or vice versa. Either, or both, of the detectors **122** and **126** may be implemented in alternative embodiments by mechanical, optical, electromagnetic transmission (e.g., implanting a radio-frequency transmitter with secondary coil **230** and detecting the strength and direction of its signal), or other detectors. Such detectors may be employed with, or instead of, the resonance frequency shift detectors described with respect to the illustrated embodiment.

Also, the division of functions of current director **124** into power adjuster **310**, current direction determiner **320**, and primary coil selector **330** is made for convenience of illustration and other distributions of these, and other, functions may be made in alternative embodiments. Also, as noted, many possible variations are possible with respect to the shape of primary coils, the number of loops in them, their orientations in planes with respect to each other and their housings, patterns in which arrays of primary coils are arranged, and other factors.

In addition, it will be understood by those skilled in the relevant art that control and data flows between and among functional elements of the invention may vary in many ways from the control and data flows described above. More particularly, intermediary functional elements (not shown) may direct control or data flows; the functions of various elements may be combined, divided, or otherwise rearranged to allow parallel processing or for other reasons; data structures may be employed to store and/or manipulate data; the sequencing of functions or portions of functions generally may be altered; and so on. Numerous other embodiments, and modifications thereof, are contemplated as falling within the scope of the present invention as defined by appended claims and equivalents thereto.

What is claimed is:

1. A transcutaneous energy transmission (TET) device, comprising:

at least one secondary coil disposable within a patient and adapted to receive transcutaneous energy transmission;

a plurality of primary coils, each adapted to be placed outside a patient and constructed and arranged to carry a time-varying current to transmit transcutaneous energy to the secondary coil; and

a controller constructed and arranged to detect the position of the secondary coil relative to each of the plurality of primary coils and to selectively provide current to one or more of the plurality of primary coils based on the detected position of each primary coil with respect to the secondary coil.

2. The TET device of claim **1**, wherein the controller comprises:

a proximity detector constructed and arranged to identify a quantity of the plurality of primary coils that are closest to the secondary coil; and

a current director, responsive to the proximity detector and electrically coupled to the plurality of primary coils, constructed and arranged to selectively direct time-varying currents through the closest primary coils.

3. The TET device of claim **2**, wherein:

the proximity detector identifies the quantity of closest primary coils utilizing a pressure sensor.

4. The TET device of claim **2**, wherein the proximity detector comprises a resonance frequency shift detector that detects a shift in inductance of one or more primary coils due to a proximity of the secondary coil.

5. The TET device of claim **1**, wherein current director directs time-varying currents to flow through the closest primary coils so that each current flows in the same direction when the secondary coil is disposed in a plane predominantly parallel to the planes of the closest primary coils.

6. The TET device of claim **1**, wherein current director directs time-varying currents to flow through the closest primary coils so that a current in each closest primary coil flows in a direction opposite to a direction of a current in an adjacent closest primary coil when the secondary coil is disposed in a plane predominantly perpendicular to the planes of the closest primary coils.

7. The TET device of claim **2**, wherein the quantity of the closest primary coils identified is a predetermined number.

8. The TET device of claim **2**, wherein the quantity of the closest primary coils identified is based on a size of the secondary coil.

9. The TET device of claim **2**, wherein the proximity detector comprises an optical sensor.

10. The TET device of claim **2**, wherein the proximity detector comprises a mechanical sensor.

11. The TET device of claim **2**, wherein the proximity detector comprises an electromagnetic transmission detector.

12. The TET device of claim **2**, wherein the quantity of the closest coils is two.

13. The TET device of claim **2**, wherein the proximity detector determines an approximate distance between one or more of the closest primary coils and the secondary coil, and the current director increases the currents through the closest primary coils when the proximity detector determines that the distance is greater than a nominal threshold value.

14. The TET device of claim **2**, wherein the current director includes a power adjuster for adjusting the amount of current directed to the closest primary coils.

15. The TET device of claim **2**, wherein the current director includes a current direction determiner for determining the directions of current supplied to two or more closest primary coils.

16. The TET device of claim **2**, wherein the current director means includes a primary coil selector for selecting primary coils to receive the current.

17. The TET device of claim **1**, wherein each of said plurality of primary coils comprises a phase and a size adapted to optimize coupling with the secondary coil.

18. The TET device of claim **1**, wherein each of the primary coils is disposed in a plane substantially parallel to, including the same plane as, a plane of each of the other primary coils.

19. The TET device of claim **1**, wherein the primary coils are disposed in two or more substantially parallel planes, including:

a first plane having one or more first-plane primary coils that, when energized, generate electromagnetic fields having one or more dead zones; and

a second plane having at least one second-plane primary coil positioned with respect to the one or more first-plane primary coils to generate, when energized, at least one electromagnetic field encompassing the one or more dead zones.

20. The TET device of claim **1**, wherein the primary coils are disposed in two or more substantially parallel planes, including:

a first plane having two or more mutually adjacent first-plane primary coils; and

a second plane having at least one second-plane primary coil positioned with respect to the two or more mutually adjacent first-plane primary coils so that the projection of a magnetic center of the second-plane primary coil on the first plane is approximately equidistant from magnetic centers of each of the two or more mutually adjacent first-plane primary coils.

21. The TET device of claim **1**, wherein the primary coils are disposed in two or more substantially parallel planes, including:

a first plane having four mutually adjacent primary coils positioned with respect to each other in a roughly square arrangement; and

a second plane having one primary coil including a second plane primary coil geometric center, the second plane primary coil positioned so that the projection of the second plane primary coil geometric center on the first plane is approximately centrally located among the four first plane primary coils.

22. The TET device of claim **1**, further comprising one or more articles of furniture housing the plurality of primary coils.

23. The TET device of claim **1**, further comprising a cardiac assist device electrically coupled to the secondary coil.

24. A cardiac-assist device comprising:

a pumping means; and

a transcutaneous energy transmission (TET) device electrically coupled to the pumping means, comprising:

a secondary coil implanted in a subject and adapted to receive transcutaneous energy transmission;

a plurality of primary coils, each adapted to be placed outside a subject and constructed and arranged to carry a time-varying current to transmit transcutaneous energy to the secondary coil; and

a controller constructed and arranged to detect the position of the secondary coil relative to each of the plurality of primary coils and to selectively provide current to one or more of the plurality of primary coils based on the detected position of each primary coil with respect to the secondary coil.

25. The cardiac-assist device of claim **24**, wherein:

the pumping means includes an artificial heart.

26. The cardiac-assist device of claim **24**, wherein:

the pumping means includes a ventricular-assist device.

27. The cardiac-assist device of claim **24**, wherein the controller comprises:

a proximity detector constructed and arranged to identify a quantity of the plurality of primary coils that are closest to the secondary coil; and

a current director, responsive to the proximity detector and electrically coupled to the plurality of primary coils, constructed and arranged to selectively direct time-varying currents through the closest primary coils.

28. The cardiac-assist device of claim **24**, wherein a phase and size of said plurality of primary coils is selected to optimize coupling with the secondary coil.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,366,817 B1
DATED : April 2, 2002
INVENTOR(S) : Robert T.V. Kung

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 1,
Line 24, reads "cochler" should read -- cochlear --;

Column 4,
Line 48, reads "simple" should read -- simply --;

Column 11,
Line 1, reads "71OB" should read -- 710B --;

Column 13,
Line 49, reads "830B and 830B" should read -- 830B and 830C --;

Column 14,
Line 15, reads "9A-9A" should read -- 9B-9B --;
Line 65, reads "fill" should read -- full --;

Column 17,
Line 19, reads "$10^{31\ 4}$" should read -- 10^{-4} --;
Line 24, reads "secondary coil 230" should read -- a primary coil 1010 --;
Line 48, delete "in";

Column 22,
Lines 8 and 13, reads "claim 1" should read -- claim 2 --.

Signed and Sealed this

Tenth Day of February, 2004



JON W. DUDAS
Acting Director of the United States Patent and Trademark Office