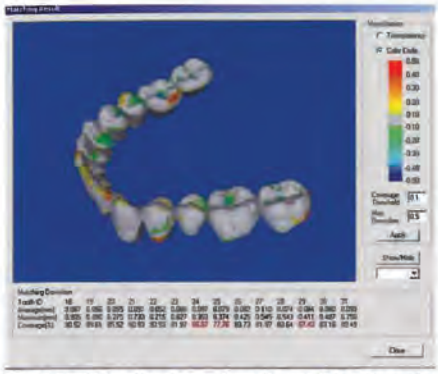


FIG 14-3 Visualization of tooth matching by color code.

Sciences International, or Hitachi) are plagued by a similar problem.

The volumetric technique yields far more data than does traditional 2-D cephalometric radiography. This gap in the amount of information may necessitate some conceptualization to superimpose the before- and after-treatment images in 3-D. For example, the cranial base landmark basion may need to be redefined in a 3-D image. The challenges of this are twofold: (*1*) the methodology of superimposition based on an abundance of 3-D features, and (*2*) the difficulty in recognizing these features.

Superimposition Tool

When a case deviates from the approved treatment plan, reprocessing is required (Figs 14-1 to 14-4). This involves a new impression, setup, ClinCheck approval, and new aligners. The clinician will want to determine the reasons why the teeth deviated from the expected target positions. In this process, the superimposition tool can perform several functions:

1. Allows a new scan of a midcourse correction (MCC) case that can be used in a best-fit comparison with the original approved treatment. A best-fit comparison of the overlapped models can reveal discrepancies between treatments.
2. Can be used to position the corrected teeth together with the original teeth based on the reference stage and reference teeth. The reference teeth can be specified manually or automatically.
3. Allows the discrepancies between the original and corrected tooth positions to be quantified and visualized (Figs 14-5 and 14-6).

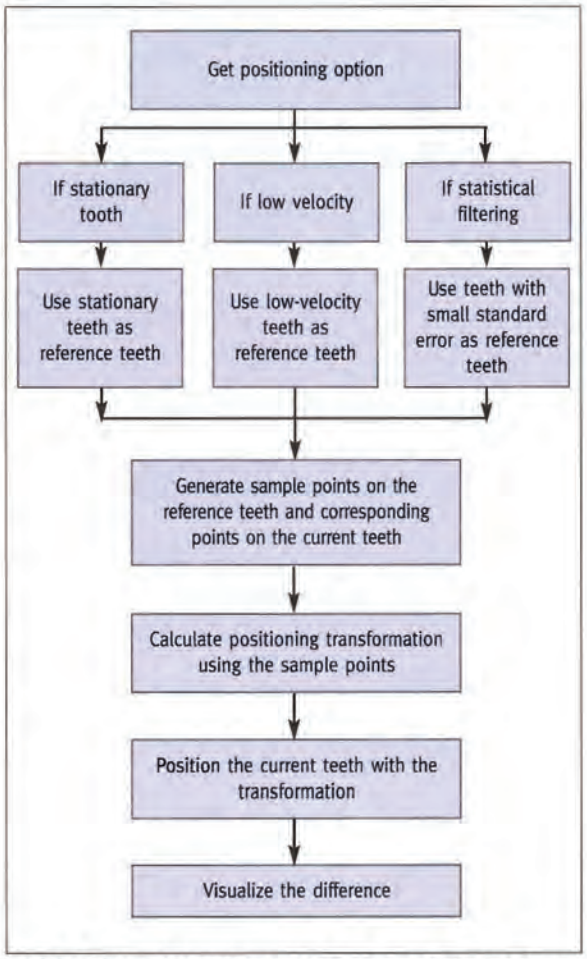


FIG 14-4 Process for positioning the new jaw in the original coordinate system.

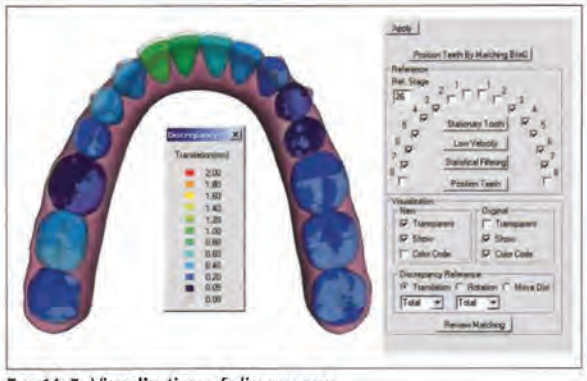


FIG 14-5 Visualization of discrepancy.

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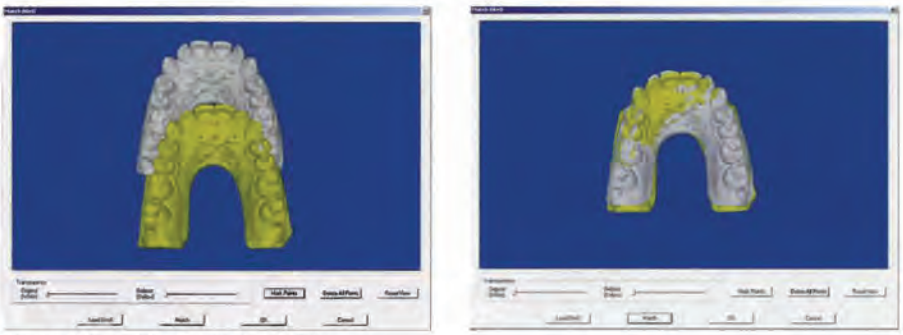


FIG 14-6 (a and b) Rugae matching.

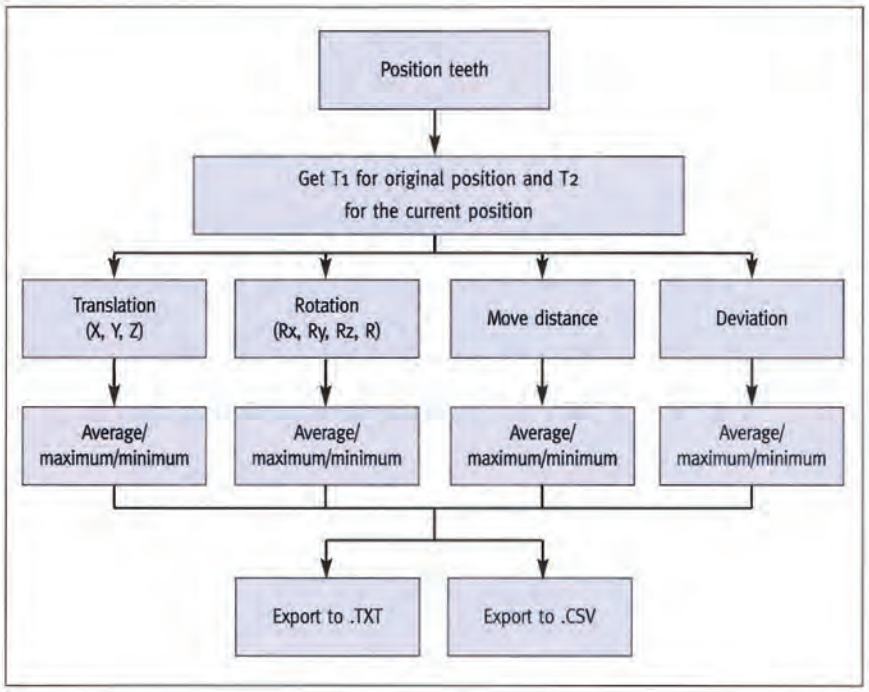


FIG 14-7 Report of analysis result. T = rigid transformation

4. Can generate a report with information focusing on the discrepancies in the location of the teeth in the original treatment and the new impression (Fig 14-7). The report is helpful in the evaluation of MCC cases.
5. Can be used to create an MCC Align data file (ADF) based on teeth matching, positioning teeth by matching original bite zero (3-D jaw model without segmentation used for initial treatment) and reboot bite zero (the same, used for MCC treatment), or by specified reference stage and teeth and target stage (Fig 14-8). Ideally, the MCC Align data file gets the treatment back on track, thus precluding the need to completely redo the case. This prevents waste of materials and allows for the use of most of the original aligners, which are augmented by any additional aligners created to correct the deviation.

Retrospective Study of Performance Index of Aligners

Align Technology was the first company to introduce a computer-designed removable orthodontic appliance. Clearly, the effectiveness of this appliance in patient care must be established by evidence-based reports. Some of these reports are described below.

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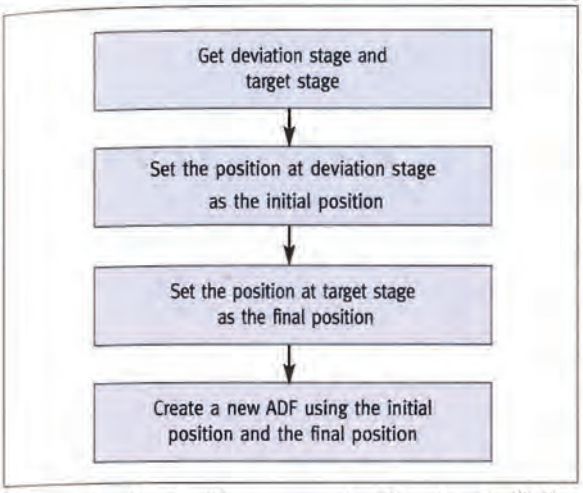


FIG 14-8 Creation of midcourse correction Align data file (ADF).

This study focused on analyzing retrospective data to compare how well aligners perform relative to traditional orthodontic treatments. Concurrently, the aim was to explore the range and predictability of each possible movement. Clinicians can thus estimate which tooth movement within a certain range has a better chance of being achieved (Fig 14-9).

Methodology

Sixty arches (30 maxillary and 30 mandibular) were randomly selected from 38 patients. Superimposition was used to match treatment files of each arch. Treatment files contained the digital models of the patient's teeth and gingiva, which were created from an impression that had been scanned and digitized.

When matching is performed, the progress scan is superimposed over the initial scan to yield a match percentage based on tooth anatomy and position. If the initial alignment of teeth is severely irregular, the outcome of the matching is not as good and, consequently, there is a greater chance of a larger measurement error in superimposition.

After teeth in the two arches are matched, Superimposition asks for a reference to relate the maxillary and mandibular arches. When the Statistical Filtering option is selected, Superimposition measures the amount of movement for each tooth by first eliminating as reference the ones that move more than one standard deviation above or below the mean of movement of all teeth. Movement is determined by the difference in position between the cur-

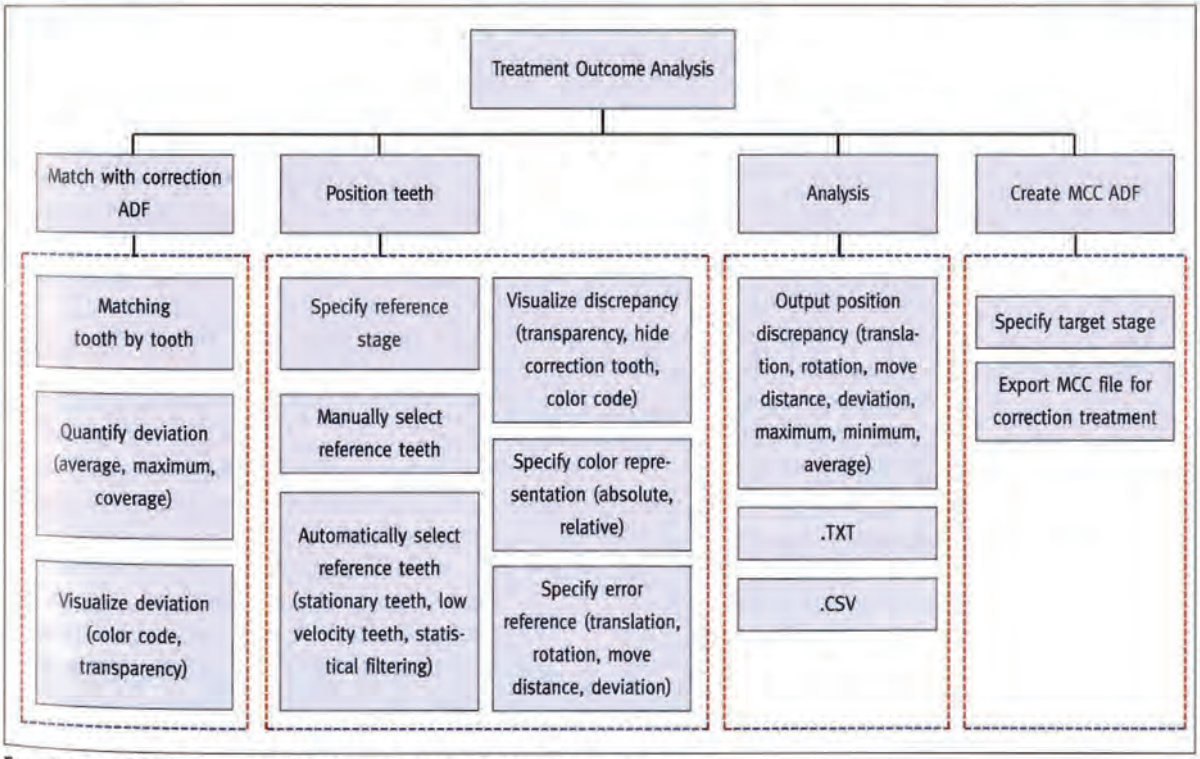


FIG 14-9 Functional summary. (ADF) Align data file; (MCC) midcourse correction.

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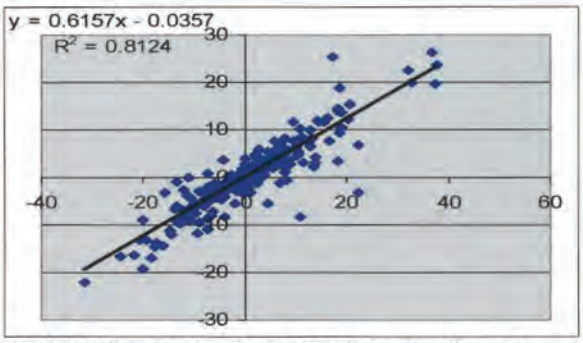


FIG 14-10 Scatter graph showing incisor rotation (degrees).

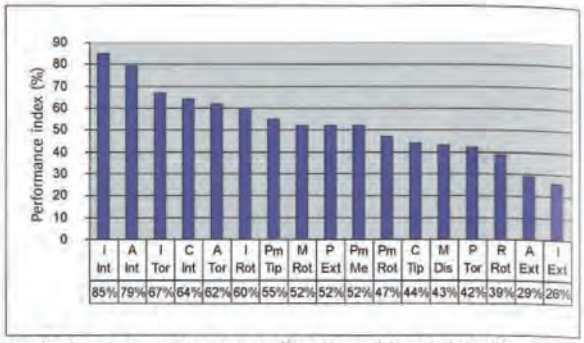


FIG 14-11 Performance index. (I) incisor; (A) anterior; (C) canine; (Pm) premolar; (M) molar; (P) posterior; (R) round teeth (canines and premolars); (Int) intrusion; (Tor) torque; (Rot) rotation; (Tip) tipping; (Ext) extrusion; (Me) mesialization; (Dis) distalization.

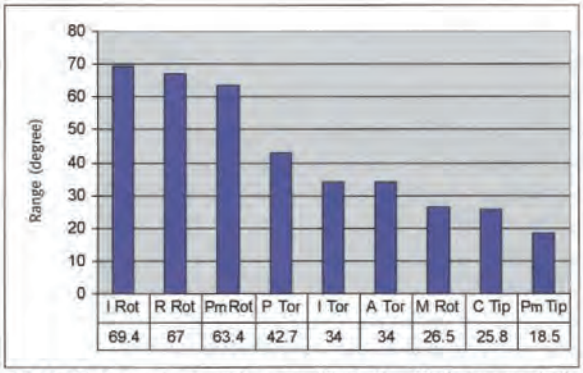


FIG 14-12 Average planned range of rotation (Rot), torque (Tor), and tipping (Tip). (I) incisor; (A) anterior; (C) canine; (Pm) premolar; (M) molar; (P) posterior; (R) round teeth (canines and premolars).

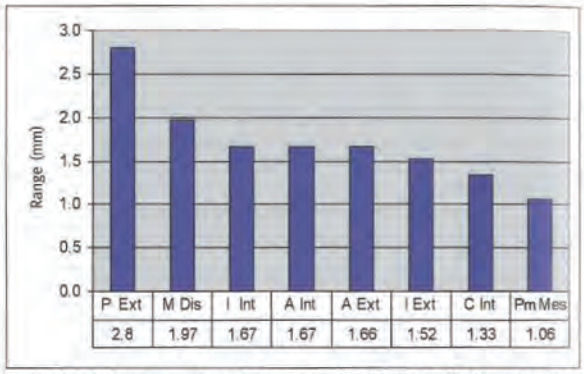


FIG 14-13 Average planned range of intrusion (Int), extrusion (Ext), distalization (Dis), and mesialization (Me). (I) incisor; (A) anterior; (C) canine; (Pm) premolar; (M) molar; (P) posterior.

rent stage and the previous one. The remaining slow or nonmoving teeth are then selected as references to measure the movement of each tooth.

A treatment stage is selected to indicate when clinical observation and simulated treatment progress deviate. The difference (of each of six movement components X, Y, Z, Rx, Ry, Rz) between the initial and progress positions is reported by Superimposition as "Achieved," whereas the "Goal" is determined by the simulation.

The amount of movement "Achieved" is plotted against that of "Goal" in scatter graphs, and trend lines are generated. Scatter graphs are then shown to demonstrate where all scattered data points are. Trend lines are generated to show the performance of the aligners. Trend lines are linear and present the best-fit straight lines for all scattered data. The performance of the aligners is represented as the slope of a trend line. The y-axis intercept signifies the amount of incidental movement that occurs when the aligners are worn. Predictability is obtained by R2, which is obtained from the regression computation of "Achieved" and "Goal" data. A scatter graph is shown in Fig 14-10.

Summary of findings and conclusion

The following groups of teeth were examined in this study: incisors, canines, premolars, molars (excluding third molars), anterior teeth, posterior teeth, and round teeth (canines and premolars). A list of tooth movements of the selected 60 arches is shown in Table 14-1. The following findings are presented in Figs 14-11 to 14-13.

1. The performance indices and coefficient of correlation of incisor intrusion and anterior intrusion show that these movements are likely to achieve the treatment goal.
2. Canine intrusion, incisor torque, incisor rotation, and anterior torque performance are average in terms of performance.

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3. Premolar tipping, premolar mesial movement, molar rotation, and posterior expansion are less likely to attain the treatment goal.
4. Anterior and incisor extrusion, round teeth and premolar rotation, canine tipping, molar distalization, and posterior torque are unlikely to achieve the treatment goal.

The performance trends presented in the results do not deviate significantly from what has been common knowledge among clinicians. The exception is posterior expansion, which is thought to be a high performance movement when clinicians use aligners.

Prospective Study of Stage-by-Stage Aligner Performance

Methodology

The evaluation of progression was achieved primarily by superimposing the original treatment with the progression scan (Fig 14-14). The Superimposition tool was used to find the discrepancy between the planned movement and the actual result.

Data preparation

The following steps were used to prepare the data: the individual scans were examined, and the scans were cut. If there were attachments on the scan, the scan was detailed to remove the attachment.

Tooth matching

In the first step of the superimposition, the tooth-matching result was displayed. If any tooth showed unusually poor matching, the tooth was excluded from the reference teeth selection.

Reference teeth selection

The Superimposition tool requires the user to select the references during positioning of the jaw. Static teeth/low-velocity teeth were selected as reference teeth whenever possible. In instances of unusual discrepancy, statistical filtering was employed.

Progression of individual teeth

The same Superimposition method was applied to each stage scan: the planned movement was derived from Stage Editor. The actual outcome was derived from the analysis report. If there was a big rotation, the coordinate system at the initial stage and the one after the movement were changed accordingly. The reported vectors may not be consistent; however, the observed teeth have single primary direction of motion. Thus, the coordinate system change has not affected the superimposition significantly. Because each individual stage motion is created from an individual jaw positioning, there may be fluctuation of values.

Table 14-1 Orthdontic movements

A Ext	Anterior extrusion
A Int	Anterior intrusion
A Tor	Anterior torque
B Mes	Premolar mesialization
B Rot	Premolar rotation
B Tip	Premolar tipping
C Int	Canine intrusion
C Tip	Canine tipping
I Int	Incisor intrusion
I Ext	Incisor extrusion
I Rot	Incisor rotation
I Tor	Incisor torque
M Dis	Molar distalization
M Rot	Molar rotation
P Exp	Posterior extrusion
P Tor	Posterior torque
R Rot	Round teeth (canines and premolars) rotation

Lag

Lag represents how much the actual treatment is progressing behind the planned movement. The superimposition analysis reports the comparison of the current stage to every stage. The closest stage is selected by comparing the amount of the discrepancy. Lag is defined by the difference between the closest planned stage and the current stage. The stages that exhibit unusual lag characteristics are reported.

Movement direction

The orientation of the planned and the actual move vectors are compared. If the motion is primarily in a single direction, (eg, y direction), the y direction motion is compared. The scale perpendicular directional motions are compared to the tangential motion.

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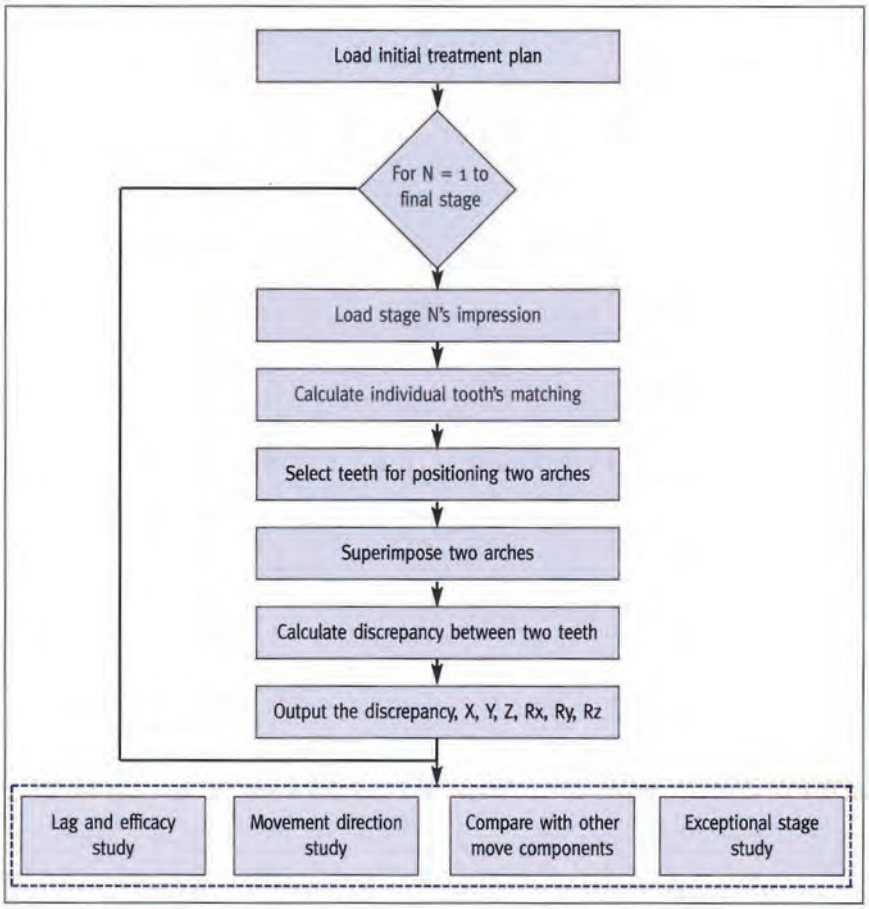


FIG 14-14 Process of progression study. (N) given stage.

TABLE 14-2 Tooth movement lag: Canine linguobuccal translation.

Stage	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Closest	11	12	13	14	15	15	16	18	18	19	21	22	22	24	25	25	25	26
Lag*	0	0	0	0	0	1	1	0	1	1	0	1	1	0	0	1	2	3

**Average lag = 10/18 = 0.56 stages.*

TABLE 14-3 Tooth rotation lag: Lateral incisor mesiodistal translation

Stage	16	17	18	19	20	21	22	23	24	25	26	27	28
Closest	16	16	16	17	17	17	18	18	19	20	21	21	23
Lag*	0	1	2	2	3	4	4	5	5	5	5	6	5

**Average lag = 47/13 = 3.62 stages.*

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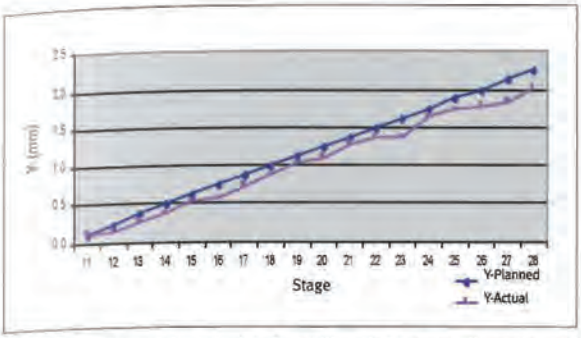


FIG 14-15 Progression study of maxillary left canine linguobuccal translation (Y).

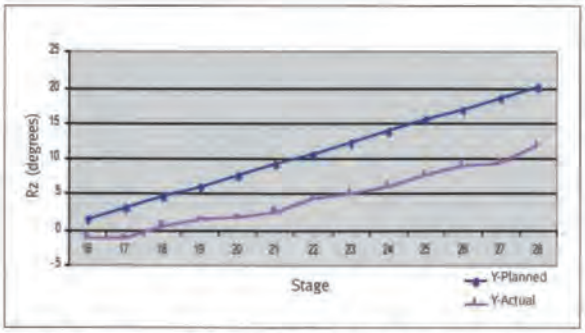


FIG 14-16 Progression study of maxillary left lateral incisor mesiodistal rotation (Rz).

Efficacy

The actual achieved motion is divided by total planned motion. The efficacy is analyzed in a single direction of motion.

Example of linguobuccal translation progression

For each stage, tooth movement has a lag. The average lag is 0.56 stages (Table 14-2). During the treatment, the maxillary left canine is moving along the y-axis as planned. The final achieved stage most closely matches planned stage 26. The achievement is 89.8% (2.02 mm/2.25 mm) (Fig 14-15). The lag at final stage is 0.23 mm.

Example of mesiodistal rotation progression

For each stage, the tooth rotation has a lag. The average lag is 3.62 stages (Table 14-3). During the treatment, the maxillary left lateral incisor is rotated around the z-axis as planned. The real final stage most closely matches planned stage 23 (Fig 14-16). The achievement is 56.2% (11.9 /20.1 degrees).

Summary

Clinically, it is safe to assume that one will get about 80% of the tooth movement seen on ClinCheck images. Thus, it is practical for the clinician to think in terms of overcorrection, and even rely on case refinement to achieve the ultimate result.

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chapter 15

VIRTUAL INVISALIGN PRACTICE

by
David Chenin, DDS

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Virtual Invisalign Practice (VIP) is a robust portion of the Invisalign website (invisalign.com). It is customized with all of the patient information from the treating clinician's practice and requires a secure log-in. VIP contains features that allow the treating clinician to quickly and easily access complete patient and order information on his or her own Invisalign cases. Thus, VIP is the means by which a treating clinician accesses his or her three-dimensional (3-D) virtual treatment setups and the method by which Align and the treating clinician can communicate with one another about specific cases. Additionally, VIP allows access to the latest clinical information and practice development material regarding Invisalign.

To access VIP, certified clinicians must first connect to www.invisalign.com. Once connected, they access VIP by going to the "Doctor" page and entering their assigned username and password. The username and password are only available to certified clinicians and provide security to the clinician's patient information in accordance with the guidelines outlined by the Health Insurance Portability and Accountability Act (HIPAA). Once the username and password have been entered, the clinician is connected directly to the VIP home page, where all of his or her patient information can be accessed. For additional privacy, clinicians can also log in directly to a patient file to provide maximum confidentiality during a consultation. This is achieved by providing the patient's first and last name (ie, John Smith) or by entering the patient case number along with the username and password.

Once a clinician gains access to VIP, he or she is directed to a personal VIP home page, which provides a quick overview of issues that require attention (Fig 15-1). Displayed here is a link to the clinician's list of patients; patients that require an action to be taken are highlighted. The Patient List page provides the clinician with a sortable listing of patients that can be organized according to parameters of the clinician's choice (Fig 15-2). The default is a list of patients with "action required," but the clinician can sort the patient list in other ways such as "currently in treatment," "by name," "with patient number," etc. Also displayed at the bottom of the home page are important notices from Align regarding the clinician's practice.

By clicking on a specific patient, the clinician is directed to the Patient File page, which provides all patient-specific information (Fig 15-3). It includes multiple orders (past and present ClinCheck modifications) for a given patient. The status of the current order is shown in blue, and an abbreviated order history section is shown in gray. From this page, the clinician may view the All History page, which details all current and past orders. Patient icons (for Patient Files, ClinCheck, Images, and Treatment Forms) allow the clinician to navigate and access all patient information (eg, radiographs or prescription and diagnosis forms) that has been uploaded online.

In the left navigation box titled "Tools and Forms," clinicians may click on Case Forms to access a new treatment form for a patient. This area allows clinicians to fill out an online prescription form and upload photographs and radiographs to Align's secure database (Fig 15-4).

Another feature, called Doctor Profile, can also be modified online. Doctor Profile permits clinicians to change their password or security question/answer, review the existing billing and shipping addresses on file, and make updates and additions quickly and easily. In addition, clinicians can indicate how they would like to manage communication with Align for matters such as billing.

Finally, clinicians can establish or edit their treatment preferences, which are used by Align to set up cases. Treatment preferences, along with the information supplied in the prescription and diagnosis form, are used by Align technicians to provide a ClinCheck that more closely meets the clinician's expectations.

In the left navigation box titled "Clinical Information," clinicians can access a wide range of clinical information to help achieve excellent clinical results. Ancillary products (eg, buttons, elastics, interproximal reduction kits, etc) can also be ordered from this location (Fig 15-5). For reference, clinicians can read the Invisalign glossary. This glossary is not designed to be all-inclusive, but is intended for use as a tool for dental professionals as they learn about the Invisalign treatment modality. Case studies are also available (Fig 15-6). In the Case Studies section, representative cases of patients treated with Invisalign are shown in detail. From diagnosis to final results, each case provides comprehensive information on treatment planning, ClinCheck, and finishing—three integral elements for getting consistent, quality treatment outcomes with Invisalign. Each case includes extensive clinical commentary, interactive ClinChecks, and full records and forms. Another feature of the Clinical Information area is the community forum, which is designed to encourage discussion and the sharing of knowledge within the Invisalign community. A valuable part of the Clinical Information area is that it provides an opportunity for clinicians and staff to earn continuing education credits online at no cost by reading case studies or helpful clinical techniques.

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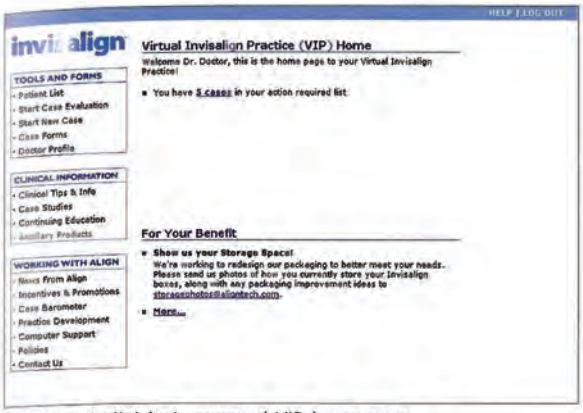


FIG 15-1 A clinician's personal VIP home page.



FIG 15-2 Patient List page.

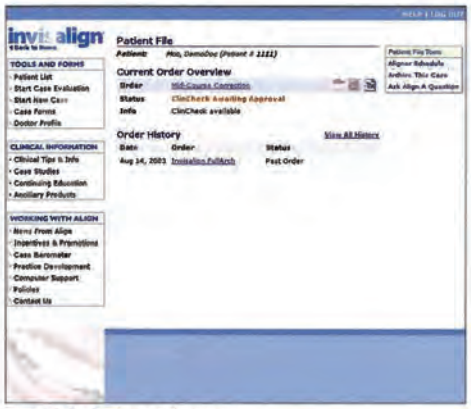


FIG 15-3 Patient File page.



FIG 15-4 Page for uploading patient radiographs to Align.



FIG 15-5 Ancillary products can be viewed and ordered.



FIG 15-6 Case Studies page, used to view records of other Invisalign cases.

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In the left navigation box entitled "Working with Align," clinicians can click on Incentives & Promotions to access a new informational area dedicated to practice development (see Fig 15-5). Additionally, clinicians can find computer-related information to help their practices stay current with the latest technologies that Align uses to communicate with clinicians. For example, recommended computer specifications are published to help clinicians make decisions about the purchase of new computer equipment.

Features valuable to Align, the clinician, and the clinician's staff or patients are added or improved every week. As a result, many other features found in VIP that have not been discussed here may be valuable to the clinician's practice. In many ways, the VIP site functions as part of the patient's chart.

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chapter 16

COMPUTER-ORIENTED DENTAL MEASUREMENTS

by
Vadim Matov, PhD

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This chapter introduces a novel measurement system implemented in the Align Technology software that is based on computer-oriented dental irregularity metrics (CODIM). Unlike the traditional measurements performed on plaster casts, measurements from CODIM are performed on three-dimensional (3-D) computer dental models produced by scanning impressions or casts or intraorally. Such models allow the introduction of a much wider variety of measurements than does the traditional manual approach.

The goal of CODIM is to provide a complete, objective, and consistent characterization of the dental irregularities captured by 3-D computer modeling. While CODIM comprises all traditional orthodontic measurement, it has the following distinctions:

- Measurements are much more accurate and detailed.
- Metrics incorporate measurements that can only be obtained through 3-D computer modeling (ie, they cannot be obtained using traditional instruments and protocols).
- Most of the measurements from CODIM are performed automatically, which makes them independent of the clinician's preferences or the skills of the technicians performing them.

Measurements from CODIM are implemented as a plug-in to two proprietary software programs integral to the Invisalign System: Treat and ToothMeasure. The measurement software, most notably ToothMeasure, provides the functionality to support the following:

- Automatic diagnosis of malocclusion with complete analysis of dental irregularities
- Evaluation of treatment plans with detection of difficult movements
- Automatic selection of arch forms for final position setup
- Validation of staging
- Collection of dental statistics for data mining

In this chapter, a new algorithmic approach to dental measurement that constitutes the basis of CODIM is introduced. The main component of this algorithmic approach is the rigorous "form measurement" definition, which is translated into software error-free.

In addition to incorporating measurements of the teeth and gingiva from 3-D dental models, CODIM utilizes several other measurements. These may be split into three groups: (*1*) shape of individual teeth, (*2*) alignment of the teeth of the same arch (intra-arch measurements), and (*3*) bite characteristics (interarch measurements). We will focus our discussion primarily on intra-arch and interarch measurements, as these are most relevant to the alignment process. The images in this chapter were created using ToothMeasure 1.0.

Dental References

In addition to the scanned geometry of the teeth and gingiva, the following set of objects is essential for the evaluation of irregularity of tooth positions. These objects are derived from the geometry and location of the teeth and serve as references for the measurements. For example, the tip of the incisor (incisor angulation) is measured (according to Andrews[1]) as the angle between the facial axis of the clinical crown (FACC) and a line below it perpendicular to the occlusal plane (called a *normal*), as seen from a facial view of the tooth. Both the FACC and the occlusal plane are references.

The main references used in CODIM are occlusal plane, FACC curve, facial plane of the clinical crown, facial axis point, middle plane of clinical crown, facial axis line, facial normal line, wire curve, arch form curve, and arch form template.

Occlusal plane

The occlusal plane is constructed for the mandibular arch. For well-aligned teeth, this is the plane that passes through the tips of the central incisors and the cusps of the first molars. For average position of the mandibular teeth, the occlusal plane sits on top of all mandibular teeth (except the canines) and passes through at least three points, two of which are the tips of the incisors (Fig 16-1).

Facial axis of the clinical crown

The facial axis of the clinical crown is the curve on the facial part of a tooth's clinical crown between the occlusal and gingival extremities. For incisors, canines, and premolars, the FACC curve is the midline of the facial part of the clinical crown. For molars, the FACC curve goes along the buccal groove. Endpoints of the FACC curve are called the occlusal and gingival points, correspondingly (see Figs 16-1 and 16-2).

Facial axis point

The facial axis point (FA point) is the midpoint of the FACC curve. For anterior teeth, the FA point is the center of the facial part of the clinical crown of the tooth (see Fig 16-2).

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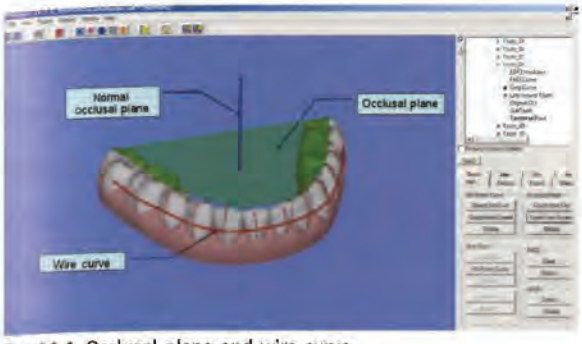


FIG 16-1 Occlusal plane and wire curve.

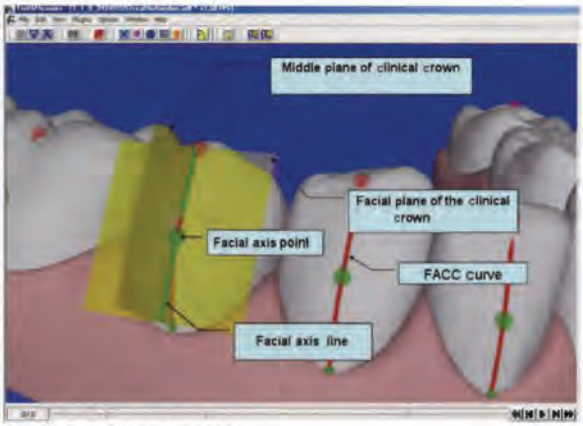


FIG 16-2 Tooth references.

Middle plane of the clinical crown

It is important to remember that the FACC curve is not a linear segment between its endpoints but rather a curve on the facial surface of the tooth. This curve is close to a middle plane of the clinical crown (MPCC) of the tooth (in nonpathologic cases), which is transversal to the facial surface of clinical crown. (see Fig 16-2).

Facial axis line

The facial axis line (FA line) is tangent to the FACC curve at the FA point. For regularly shaped anterior teeth, the FA line passes through the FA point in the direction of the FACC curve, but otherwise has no other common points with the tooth (see Fig 16-2).

Facial plane of the clinical crown

The facial plane of the clinical crown (FPCC) is tangent to the facial surface of a clinical crown at the FA point. As with the FA line, the facial plane passes through the FA point but otherwise has no common points with the tooth (see Fig 16-2).

Facial normal line

The facial normal line (FN line) is perpendicular to the FA line on the facial plane at the FA point.

Wire curve

The wire curve is a smooth curve passing through the FA points of all teeth of the same arch (see Fig 16-1).

Arch form curve

The arch form curve is a particularly important reference. It provides a measurement of how well the teeth are aligned within the same arch with respect to rotations along the vertical axis and prominence. The arch form curve in 3-D can be constructed in several different ways. In early versions of the ToothMeasure software, the arch form curve was constructed in one of two ways:

- The wire curve was made symmetric and convex from the occlusal view.
- One of the arch form templates (see below) was scaled to fit the case under consideration.

Arch form curve template

The arch form curve template is one of several typical arch form curves collected from the Align Technology database of treated and approved cases. Although the arch form curves differ from patient to patient, they can be grouped into clusters of arch forms of similar shape. One arch form curve that is representative of each cluster becomes an arch form template. Arch form templates are used as arch form curves for new patients after they are appropriately scaled to the patient's arches.

Intra-arch Measurements

Intra-arch measurements are measurements applied to the teeth of the same arch. These measurements provide numeric values that characterize the alignment of teeth within the arch, as well as individual characteristics of the teeth. Intra-arch measurements can be divided into several groups: tooth shape characteristics, tooth angular position with respect to the references (tip, torque, rotation), tooth linear position with respect to the references (prominence, level), crowding and spacing, degree of anterior teeth alignment, and degree of posterior teeth alignment.

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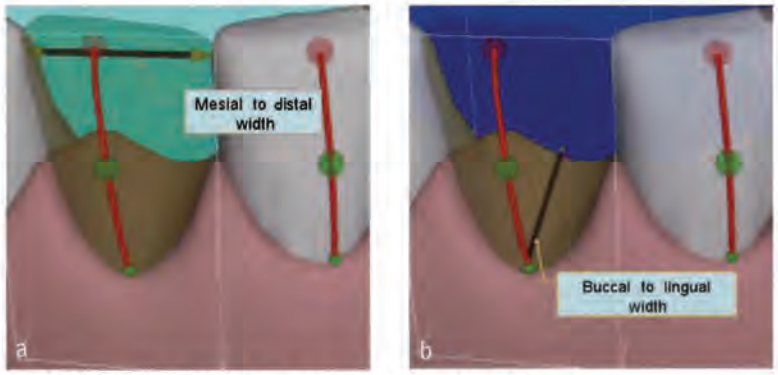


FIG 16-3 Mesial-to-distal (*a*) and buccal-to-lingual (*b*) widths.

All intra-arch measurements are described below except for the last two groups, which will be described after relevant tooth anatomic features are introduced.

Tooth shape characteristics

The measurements for individual teeth capture the basic features of crown shapes. There are common characteristics for different types of teeth. Tooth shape characteristics are important since the efficacy of the aligners depends on the aligner's grip, which in turn depends on the shape of the crown (as well as on the level of crowding).

The following common tooth characteristics are measured by ToothMeasure and other Align Technology software applications: mesial-to-distal width, buccal-to-lingual width, and crown height.

The *mesial-to-distal width* of a tooth is the distance between the horizontal points of the tooth projected onto the FPCC. This distance is measured in the direction of the normal middle plane. In other words, the mesial-to-distal width is the width of a tooth as it seen from the facial direction (Fig 16-3a).

The *buccal-to-lingual width* value is the distance between the innermost and outermost points of the tooth projected onto the MPCC. This distance is measured in the direction of the normal facial plane. In other words, the buccal-to-lingual width is the width of a tooth's profile (Fig 16-3b).

Crown height is the length of the crown measured in the direction of the FACC line; it is the height of a tooth's clinical crown.

Tooth angular position

The following measurements reflect the angular position of each tooth relative to the references: crown angulation (tip), crown inclination (torque), and crown rotation (around the tooth axis). Note that tooth angular characteristics make sense only with respect to the references. They are meaningless for a tooth taken in isolation.

Crown angulation (tip) is the angle between the FA line and the upward normal to the occlusal plane. The angle is measured as projected onto the FPCC. See Fig 16-4, where the normal to the occlusal plane has been translated to FA point.

Crown inclination (torque) is the angle between the FA line and the upward normal to the occlusal plane. The angle is measured in projection onto the MPCC. See Fig 16-5, where the normal to the occlusal plane has been translated to FA point.

Crown rotation is the angle between the FN line and the arch form curve. The angle is measured in projection onto the occlusal plane. See Fig 16-6, in which the tangent line to the arch curve is represented by a red arrow.

Tooth linear position

The following measurements reflect the linear position of each tooth relative to the references: crown level, crown prominence, and curve of Spee. As with tooth angular position, tooth linear position measurements make sense only with respect to references and are meaningless for a tooth taken in isolation.

The *crown level* is the distance from the occlusal endpoint of the FACC curve to the occlusal plane. The distance is measured along the normal to the occlusal plane in the direction from the dental arch. Crown level is associated with the curve of Spee, which reflects how far from planar position the tips of the teeth are.

Crown prominence is the distance from a tooth's FA point to its arch form curve. The distance is measured after both FA point and arch form curve are projected onto the occlusal plane. This measurement can have a positive

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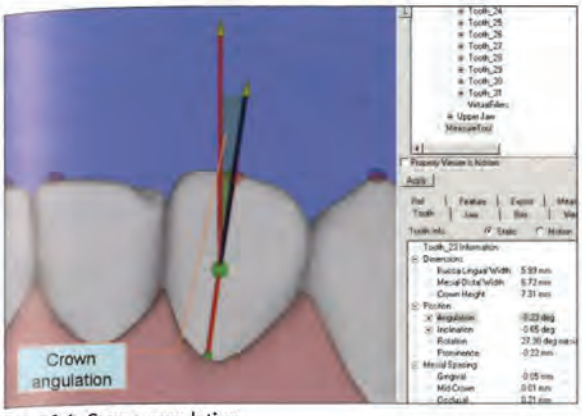


FIG 16-4 Crown angulation.

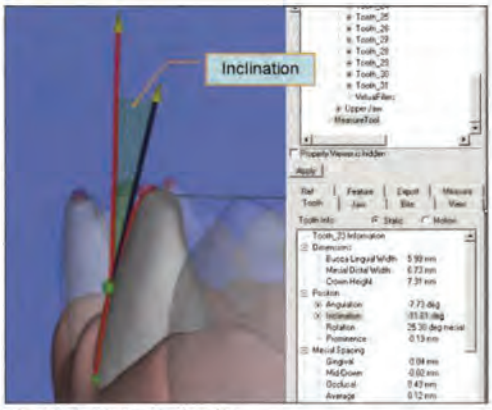


FIG 16-5 Crown inclination.

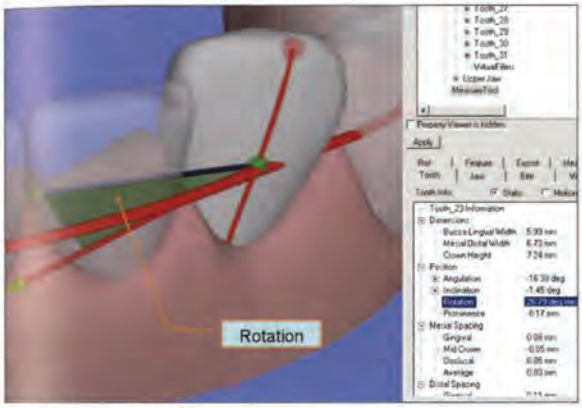


FIG 16-6 Crown rotation.

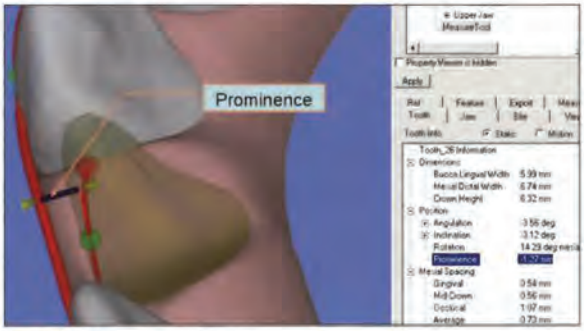


FIG 16-7 Crown prominence.

or negative value. A positive crown prominence value corresponds to FA points located outside the arch form curve, whereas a negative value corresponds to points inside the curve (Fig 16-7).

The *curve of Spee* is a smooth curve that connects the tips of the teeth of the same arch, where the tip is a point closest to the occlusal plane.

Crowding and spacing

Crowding is a measure of tooth overlap as viewed from the buccal direction. Elimination of crowding is one of the primary goals of orthodontics—a goal that requires precise and comprehensive measurements. Spacing is a measure of the distance between adjacent teeth. Note that crowding and spacing are not opposite notions: teeth can be crowded and spaced at the same time. For example, two teeth can overlap when viewed from the buccal direction and yet also be far apart when viewed from the occlusal direction (Fig 16-8). Crowding values can be negative. Negative crowding corresponds to a gap between the teeth. Crowding and spacing are measured for all pairs of adjacent teeth.

The measurement of crowding and spacing for a pair of adjacent teeth is illustrated below. These measurements are called *local crowding* and *local spacing* to distinguish them from *global crowding*, which is the sum of all values of local crowding of the teeth of the same arch.

Local crowding is measured as follows: the mesial and distal extreme points of each tooth are projected onto the arch form curve. After projection, the mesial and distal extreme points of a tooth are considered as the endpoints of the interval along the arch form curve. These intervals for two adjacent teeth can overlap or be spaced apart. In the case of overlap, the length of the overlap between the intervals is a measure of local positive crowding (Fig 16-9).

If the two intervals are apart (which corresponds to a gap between the teeth), then the length of the interval between them is a measure of local negative crowding (Fig 16-10).

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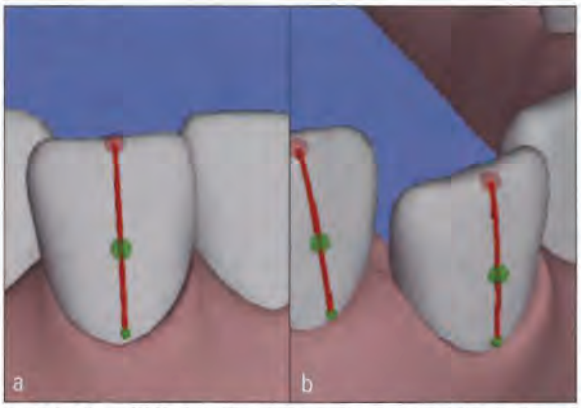


FIG 16-8 (a and b) Crowding and spacing as viewed from buccal and occlusal directions.

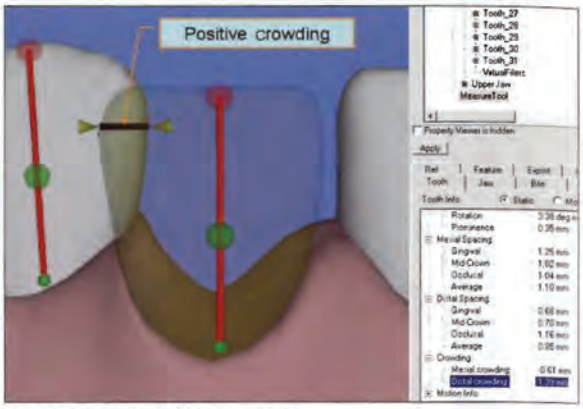


FIG 16-9 Local positive crowding.

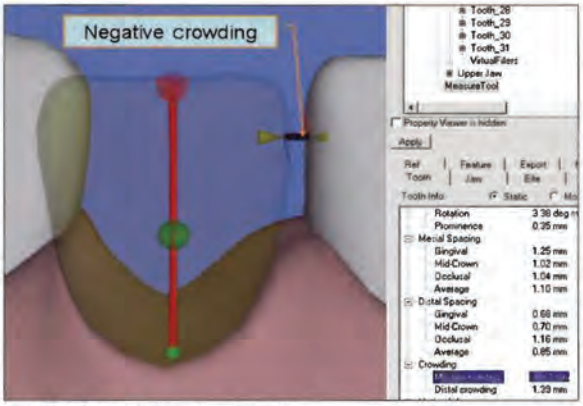


FIG 16-10 Local negative crowding.

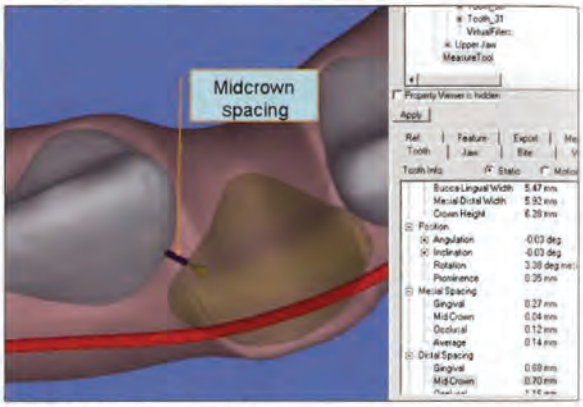


FIG 16-11 Midcrown spacing.

Local spacing is computed as follows: each tooth is split into several slices along its long axis. Each value in the set is the shortest distance between the corresponding slices of the adjacent teeth. In ToothMeasure 1.0, the number of slices is preset to three and the spacing values are called gingival spacing, midcrown spacing, and occlusal spacing (Fig 16-11).

Anatomic Dental Features

Dental features allow computing of the characteristics of alignment of teeth within one arch (intra-arch alignment), as well as characteristics of bite or the degree of malocclusion between the arches (interarch alignment).

For measurement purposes, two types of features are considered: pointed features and elongated features. Pointed features are described by the center point of a tooth and the region around this point. Cusps are an example of a pointed feature. Elongated features are described by a tooth's center curve and the region around it. Grooves and ridges are examples of elongated features. Dental anatomy and morphology have classified several hundred different dental features. Not all of these features are required for measurements. The following pointed features are used for measurement of malocclusion and misalignment: canine cusps, buccal/lingual premolar cusps, mesiobuccal/lingual molar cusps, and distobuccal/lingual molar cusps. Elongated features used for these measurements include incisor and canine ridges, central premolar grooves, and central and buccal molar grooves. Figure 16-12 illustrates the mandibular arch with all relevant features marked.

In addition to pointed and elongated features, a third type of anatomically distinctive feature plays an important role in the measurement of malocclusion. This feature represents different regions of a tooth. For orthodontic measurements, we use only occlusal and interproximal regions. Figure 16-13 illustrates occlusal regions of the maxillary arch.

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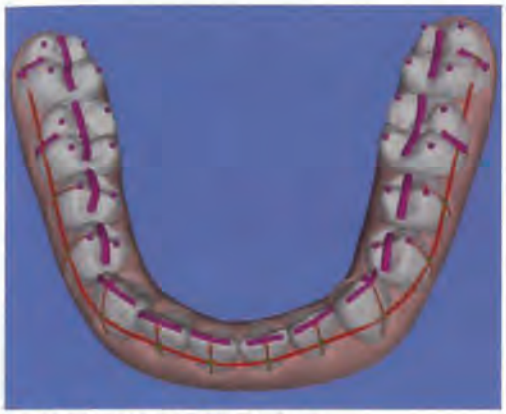


FIG 16-12 Mandibular arch features.

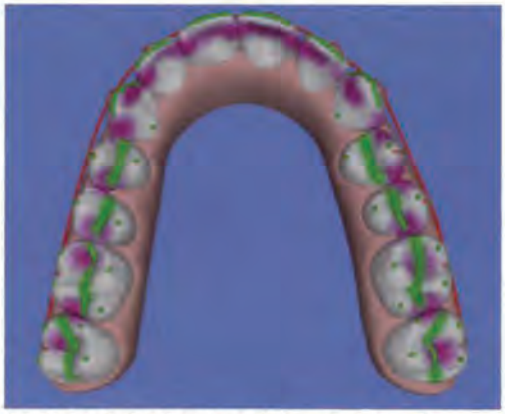


FIG 16-13 Occlusal regions of the maxillary arch.

Intra-arch Alignment Characteristics

The measurements used in ToothMeasure to characterize the alignment of teeth within one arch are described below. These measurements differ from the ones described above in two important aspects: direct utilization of anatomic features and global (versus local) alignment characteristics.

The quality of global intra-arch alignment is measured by anterior alignment characteristics, posterior alignment characteristics, and interproximal contacts.

Anterior alignment characteristics are defined by incisor ridge angles, which are the angles between the ridge and the tangent to the arch form curve. The angle is measured after both the incisor ridge and the arch form curve are projected onto the occlusal plane. The tangent to the arch form curve is computed at the closest point to the midpoint of the ridge (Fig 16-14).

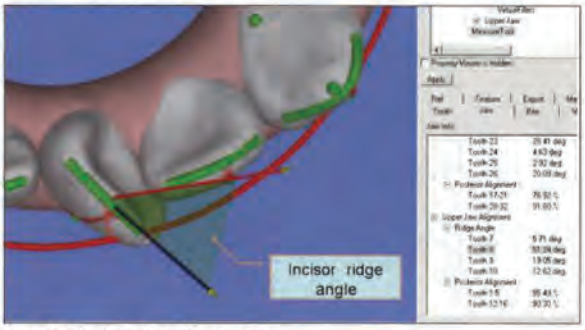


FIG 16-14 Anterior alignment.

Mandibular posterior alignment characteristics are expressed in terms of left and right perimeter curves. The perimeter curves are smooth curves that connect the left or right mesiobuccal and distobuccal cusps of the molars and the corresponding (ie, left or right) buccal cusps of the premolars. Perimeter curves constitute the outer boundary of the arch in the posterior region. Mandibular posterior alignment characteristics measure the alignment of the perimeter curves relative to the arch form curve. Mathematically, the value of the mandibular posterior alignment characteristics is (Dl – Ds)/Dl, where Dl and Ds are the longest and shortest distance between the corresponding perimeter curve and the arch form curve.

Maxillary posterior alignment characteristics are expressed in terms of left and right core curves. The core curves are smooth curves connecting the left or right central grooves of molars and premolars. Perimeter curves constitute the "middle curve" of the arch in the posterior region. Maxillary posterior alignment characteristics measure the alignment of the core curves relative to the arch form curve. The value of each of two maxillary posterior alignment characteristics is (Dl – Ds)/Dl, where Dl and Ds are the longest and shortest distance between the corresponding core curve and the arch form curve.

Interproximal contacts are a measure of the spacing between adjacent teeth (see the description above).

Interarch Measurements (Bite Characteristics)

Interarch measurements describe the relative position of the maxillary and mandibular dental arches. Their values reflect different aspects of the quality of the bite. Interarch measurements implemented in ToothMeasure fall into the following groups: occlusal contacts, occlusal relationship, anterior relative position, and relative discrepancy.

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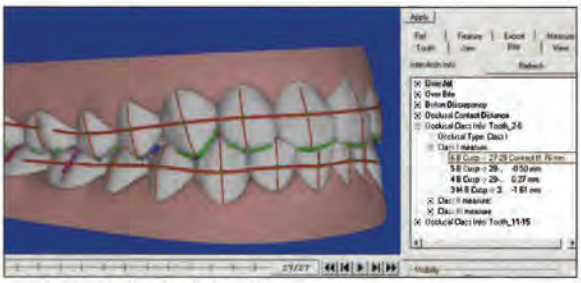


FIG 16-15 Occlusal relationship.

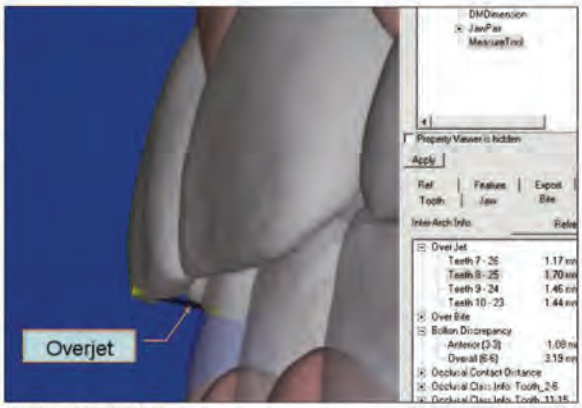


FIG 16-16 Overjet.

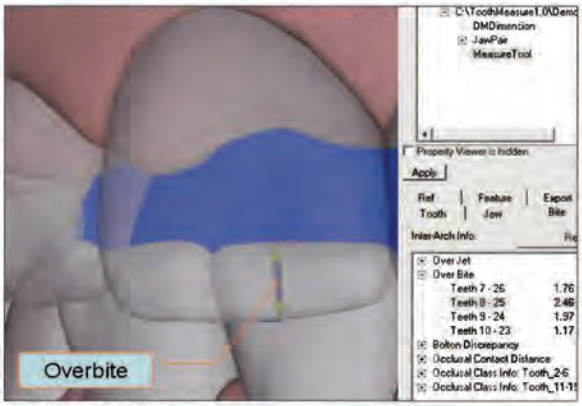


FIG 16-17 Overbite.

Measurements in these groups capture all commonly used bite characteristics and augment them with computational algorithms, providing a level of accuracy and detail that is impossible with traditional manual measurements.

Occlusal contacts

Occlusal contact of the mandibular premolars or molars is the set of distances of the buccal cusps to the central groove of the opposing tooth. Similarly, occlusal contact of the maxillary premolars or molars is the set of distances of the lingual cusps to the central groove of the opposing tooth. Occlusal contact of the mandibular anterior teeth (incisors and canines) is the set of distances from the ridges to the occlusal surfaces of the maxillary anterior teeth.

Occlusal relationship

Occlusal relationship measurements evaluate the magnitude of deviation from Class I, Class II, or Class III relationships. The measurements for a particular class of malocclusion compare a patient's relative interarch relationships to an ideal position for this class. After all the measurements are performed, the class of the bite is determined by proximity of the measured values to the ideal values for this class. Note that bite can be of a different class on the left and on the right.

Class I occlusal relationships comprise the following measurements, all of which are measured along the arch curve:

- Distance from the maxillary canine cusp tip to the embrasure contact between a mandibular canine and the adjacent premolar
- Distance from the buccal cusp of the maxillary first premolar to the interproximal contact between the mandibular premolars
- Distance from the buccal cusp of the maxillary second premolar to the interproximal contact between the mandibular premolar and first molar
- Distance from the mesiobuccal cusp of the maxillary first molar to the buccal groove of the mandibular first molar
- Distance from the mesiobuccal cusp of the maxillary second molar to the buccal groove of the mandibular second molar.

Class II occlusal relationships comprise the following measurements, all measured along the arch curve:

- Distance from the mesiobuccal cusp of the maxillary first molar to the embrasure or interproximal contact between the mandibular second premolar and the first molar
- Distance from the mesiobuccal cusp of the maxillary second molar to the embrasure or interproximal contact between the mandibular first molar and the second molar.

Class III occlusal relationships comprise the following characteristics and measurements:

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- Mandibular premolars are extracted
- Distance from the buccal cusp of the maxillary second premolar to the buccal groove of the mandibular first molar (measured along the arch curve)

It is important to understand the distinction between occlusal contact and occlusal relationship. Occlusal contacts measure how close the occlusal regions come together in a vertical direction, whereas occlusal relationship measures the distance between the intended occlusal contacts along the arch curve (Fig 16-15).

Anterior relative position

The group of anterior relative position measurements comprises overjet and overbite. Different sources provide different definitions for overbite and overjet. Below are the definitions used within ToothMeasure.

Overjet is defined for each of the mandibular incisors as well as for the mandibular anterior region as a whole. For an incisor, overjet is the distance from the midpoint of the incisor's ridge to the surfaces of the maxillary incisors. The distance is measured perpendicular to the mandibular arch form curve and parallel to the occlusal plane (Fig 16-16). The overall overjet is the average of the overjets of the two central incisors.

Overbite is defined for each of the mandibular incisors and for the mandibular anterior region as a whole. For an incisor, overbite is the proportion of vertical overlap with the maxillary anterior region to the height of the incisor's crown. This proportion is computed as the ratio of the distance between the midpoint of the incisor's ridge and the closest point on the ridges of the maxillary incisors to the incisor's crown height. The distance is measured in a vertical direction that is perpendicular to the occlusal plane (Fig 16-17). The overall overbite is the average of the overbites of the two central incisors.

Relative discrepancy

Relative discrepancy comprises midline discrepancy and Bolton discrepancy. Discrepancies express the misfit of maxillary and mandibular arches with respect to their sizes.

Midline discrepancy is the distance between the midlines of the mandibular and maxillary arches as measured along the arch. This measure shows how far the teeth have to be moved laterally to establish a common midline.

Bolton discrepancy measures the mismatch of the perimeter of the arches. Bolton discrepancy has two values: 3-to-3 and 6-to-6. A 3-to-3 Bolton discrepancy is defined as follows: Let R be the ratio of the mandibular 3-to-3 perimeter to the maxillary 3-to-3 perimeter. If $| R - 0.772 | < 0.001$, then 3-to-3 Bolton discrepancy is considered to be zero; otherwise 3-to-3 Bolton discrepancy is equal to the product of the maxillary 3-to-3 perimeter and $(1.0 - R/0.772)$. If Bolton discrepancy is greater than zero, then its value shows 3-to-3 maxillary excess; otherwise it shows 3-to-3 mandibular excess.

The formula for 6-to-6 Bolton discrepancy is similar to the one for 3-to-3, except for the constants. A 6-to-6 Bolton discrepancy is defined as follows: Let R be the ratio of the mandibular 6-to-6 perimeter to the maxillary 6-to-6 perimeter. If $| R - 0.913 | < 0.001$, then 6-to-6 Bolton discrepancy is considered to be zero; otherwise 6-to-6 Bolton discrepancy is equal to the product of the maxillary 6-to-6 perimeter and $(1.0 - R/0.913)$. If Bolton discrepancy is greater than zero, then its value shows 6-to-6 maxillary excess; otherwise it shows 6-to-6 mandibular excess.

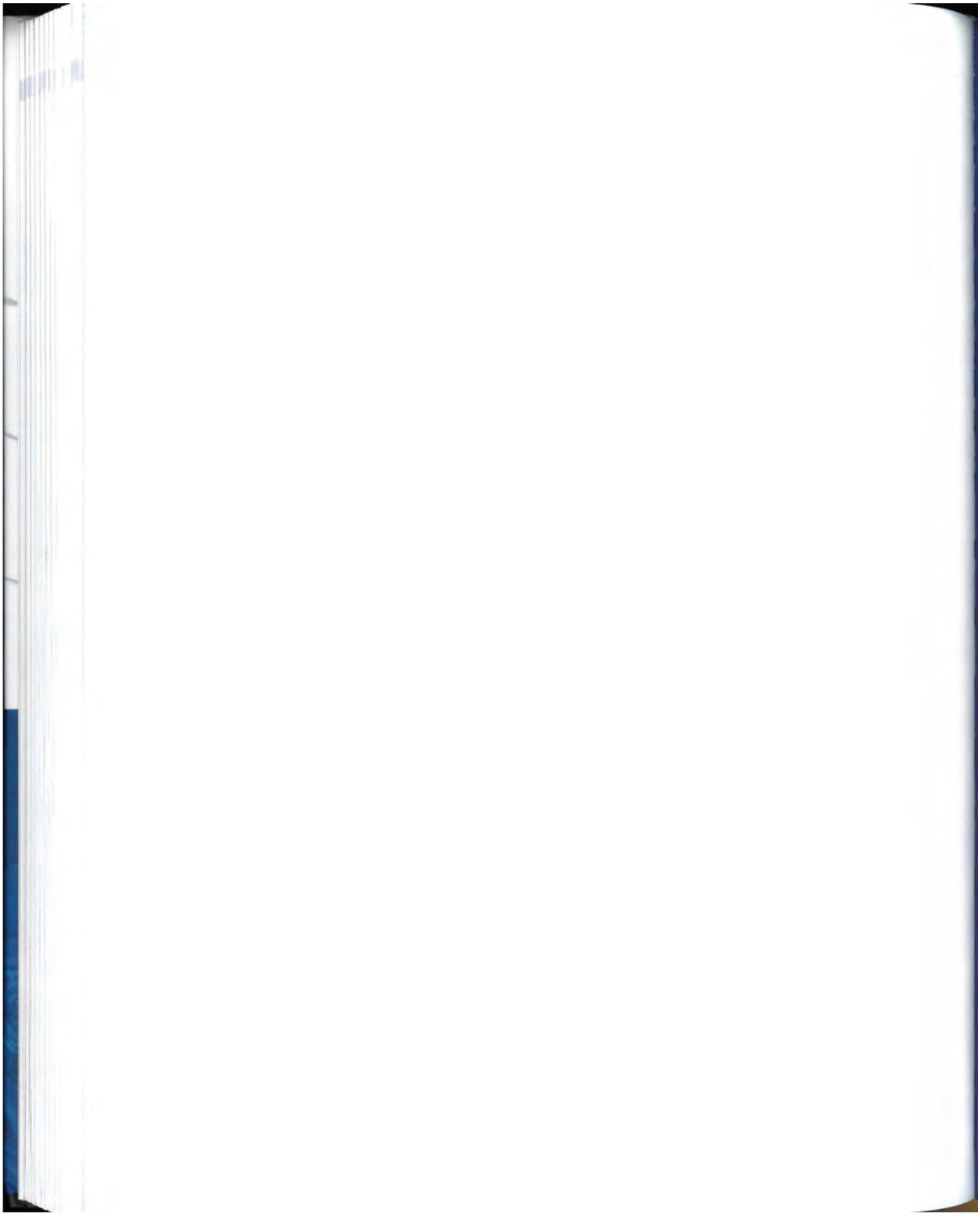
Conclusion

Besides its value in software implementation, computer-oriented dental irregularity metrics (CODIM) has much broader applications as one of the possible standards of exchange for dental data. Standard dental indices like Peer Assessment Rating (PAR) and the Objective Grading System for Dental Casts and Panoramic Radiographs can be computed from the measurement provided by CODIM. Moreover, since these computations are human independent, calibration of the person collecting the measurements is not required.

Reference

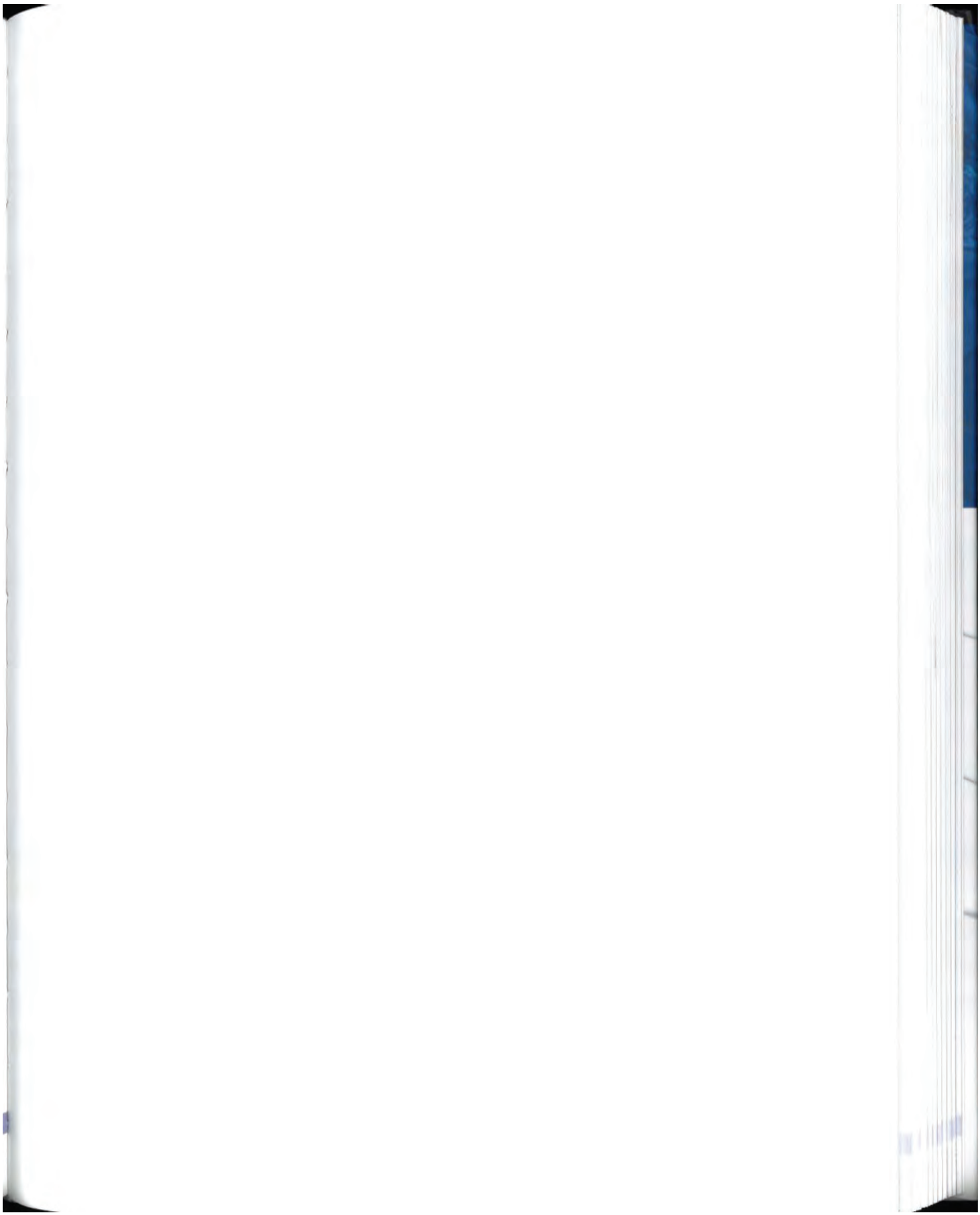
1. Andrew LF. Straight Wire: The Concept and Appliance. San Diego: L. A. Wells, 1989:14.

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SECTION III

PERFORMANCE CHARACTERISTICS OF THE INVISALIGN SYSTEM



chapter 17

MECHANICS OF TOOTH MOVEMENT WITH INVISALIGN

by
Andrew Beers, PhD and Trang Duong, DDS

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Biomechanics in orthodontics is the study of the response of periodontal apparatus to forces applied to it. The direction, degree, distribution, and duration of mechanical forces affect the periodontal response. Orthodontic tooth movement is the net result of the reaction of supporting periodontal apparatus. It is understood, however, that forces acting upon the periodontal tissues are complex and vary by the minute.[1,2] It is indeed very difficult to visualize, let alone to define, the total force system generated by the orthodontic appliances, as multiple teeth are interconnected by the orthodontic appliance in a dynamic environment.

Control of Tooth Movement

Fundamentally, tooth movement is controlled by a selective combination of forces. Any orthodontic appliance will produce an assortment of effects. Some effects are advantageous and produce the desired end result, whereas many others are undesirable, can lead to uncontrolled tooth movement, and add problems during treatment.[1,2] An understanding of such interactions allows the clinician to properly place forces and use auxiliaries that can minimize or eliminate the unwanted reactive forces.[3]

Every orthodontic appliance generates loads through different means. The Invisalign aligner is no different in this respect. This chapter and those that follow examine the mechanics of the Invisalign System and discuss it based on what is known about the mechanics of traditional fixed orthodontic appliances.

Tooth Movement with Fixed Appliances

Any type of orthodontic tooth movement requires force application. Much can be found in the literature describing the initial forces generated by fixed appliances upon their insertion. Yet, there is no consensus on the optimal force magnitude for orthodontic tooth movement; forces ranging from 2 to 30 kPa, however, have been reported. In general, translation, root torque, rotation, and extrusion require heavy forces of 50 to 150 g; tipping requires medium forces of 50 to 75 g; and intrusion requires light forces of 10 to 25 g.

Ideal force levels for orthodontic tooth movement should be high enough to stimulate cellular activity without occluding blood vessels in the periodontal ligament. The simplest form of orthodontic tooth movement is tipping upon application of a single force. Subsequently, the tooth rotates around its center of resistance. Translation, on the other hand, requires application of two or more force systems. These two systems work to balance the ratio between the moment produced by the force applied to move the crown and the counterbalancing moment produced by the couple used to control root position. The simplest way to determine how a tooth will move with fixed appliances is to determine the ratio between the moment created when a force is applied to the crown of a tooth and the counterbalancing moment generated by a couple within the bracket. In the orthodontic literature, the relationship between the force and the counterbalancing couple is termed the *moment-to-force ratio* (M/F). Moment-to-force ratios of 1 to 7 produce controlled tipping, whereas ratios of 8 to 10 result in bodily movement, and ratios greater than 10 affect the root torque.

In addition to the forces created by the archwire configuration, frictional resistance between the archwire and the bracket slot should be considered. To generate moments of a couple in orthodontics so as to control root position, rectangular wires are used; the wires need to be twisted (placed in torsion) in the bracket slot. Almost every force applied in the oral environment is complex because it is under the influence of biologic variation and the effects in three planes of space.[4] Because of these numerous and unknown contributing factors, exact force systems in fixed appliances have never been reported.

With Invisalign, the system is even more complicated because there is no exact point of force application. The aligner covers the entire surface of the crown: the point of force application depends on the anatomy of the tooth, the properties of the material, the fit or adaptation of the aligner over the tooth, and the amount of activation programmed into the aligner. Much is still to be understood. Chapter 18 discusses such forces generated in vitro.

Challenges of Studying Biomechanics with the Invisalign Appliance

The design of the Invisalign aligner makes studying its mechanics a formidable challenge. At first approximation, it appears straightforward because the position and orien-

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tation of each tooth are specified over the course of the treatment. The forces associated with a planned treatment can be either measured or simulated by a computer system without the need to further involve the patient. Furthermore, these planned forces can be compared to the results of the actual treatment because the set of Invisalign appliances fully specifies where the teeth should be at each stage of the treatment. But there are several challenges in understanding the mechanics of the aligners. The most obvious challenge is that, like many removable appliances, it is not rigidly affixed to the teeth on which it operates. This could lead to more complex interactions between the aligner and the teeth, such as slipping motions where the contact points between the aligner and the teeth change dynamically. This can also make the exertion of what we conceptually think of as "pulling" forces more difficult.

Another challenge arises from the complex shape of the appliance itself. It fits snugly over the teeth and derives its ability to apply forces almost anywhere on a tooth from this snug fit. But it is difficult to conceptualize where exactly the appliance contacts the teeth, and from there what net forces and moments result from all of those contacts. This situation is further complicated by the wide variety of actual tooth shapes, which makes the understanding of the interaction between the aligner and the teeth a patient-specific task. Also, each successive appliance is a different shape, and understanding the interaction between tooth and appliance in one stage does not necessarily provide insight into the next.

A further complication results from how the appliance is made and used. ClinCheck images prescribe the resultant individual tooth positions with each aligner wear. The plastic appliances are then manufactured accordingly. While the computer-modeled tooth positions could provide an understanding of the force interactions, it must also be considered that any deviations the teeth make from the ClinCheck-predicted locations may change the force systems between the aligner and the tooth. For example, if the tracking is lost, then the ill-fitting aligner will apply intrusive forces. As seen above, intrusion requires very light forces. Unfortunately, once intruded, the tooth cannot be recaptured in the aligner without the use of auxiliary force modules, such as vertical elastics and the like.

It is clear that such questions as "What is the optimal force level per aligner?" and "How can the complex surface-and-force interactions be studied?" need to be answered to enhance aligner performance and reduce reliance on the clinician for a successful treatment outcome.

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chapter 18

APPLICATIONS OF MECHANICS WITH INVISALIGN

by
Heng Cao, PhD and Trang Duong, DDS

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Conceptual Models

Unlike with fixed appliances, the forces that move teeth with aligners are generated by the aligner material. Moreover, these forces are highly controlled for the distance teeth are to be moved. It is generally accepted that the aligner tray generates roughly 50 g of force upon initial placement. In time, this force level decreases, but teeth still move into the positions shown by the Treat software.

Actual tooth position is defined as the position of the tooth in the mouth, whereas the beginning position captured in the polyvinyl siloxane (PVS) impression is called the *initial position*. In contrast, the planned position of the teeth is defined as the *virtual position*, which is determined using Treat. Naturally, these virtual positions are determined by the clinician with the consent of the patient within the framework of what is biologically possible.

The final position of the teeth can be achieved in individual small movements called *stages*. After each stage, the teeth are at a position closer to the final position. For reasons of the flexibility of the aligner material and the variation in the response of supporting periodontal apparatus, tooth movement lag (ie, the actual position of teeth being behind the planned position) has been shown to occur. Since the planned position is always ahead of the actual position, there would be a displacement between the two in a reference Cartesian coordinate system. This discrepancy exerts a certain amount of force along some direction on certain teeth. The interaction between the force the aligner exerts on the teeth and the resultant reaction of the teeth is shown in Fig 18-1.

Because of the variability of wear time and the material properties of the aligner, the force exerted by the aligner is not constant. It actually decreases significantly during the 2-week wear time. The instantaneous response to the force is seen mainly in the periodontal ligament (PDL) and gingiva. The viscoelastic properties of the PDL (see chapter 19) dampen and alleviate the force. The rapid decline in the aligner force shown is due to this dampening effect (Fig 18-2).

The relationship between the shock-absorbing capacity of the PDL and the physical properties of bone explains the nature of tooth movement. When the PDL is compressed to its minimal volume, the reaction then comes from bone tissue. The remodeling of bone is relatively slower than the deformation of soft tissue because bone tissue is more rigid. The reaction from bone, therefore, is continuous for hours and even days. Simultaneously, the stress relaxation that occurs in the aligner material also reduces the force magnitude. After an aligner is worn for one stage (normally 2 weeks), the teeth move to a new position. Because of the variability in the response of the teeth and the changes in the stress relaxation of the aligner material, the forces placed on the teeth will change over the course of the 2 weeks.

Tooth Movement Model

To understand how aligners work to move teeth and how to improve the efficiency and efficacy of the appliance, it is necessary to understand how teeth move spatially and temporally with aligners. A model was developed to evaluate how tooth movement occurs with aligners. The model assumes that forces and torque applied on the teeth by the aligner can be determined by experimental and finite element analysis (FEA) and was designed to understand the characteristics of the Invisalign appliance and improve its performance. The primary goal of the model was to evaluate the deviation of the actual tooth position from the prescribed treatment goal. The model was not designed to answer questions on a biologic level (such as what happens within the PDL or to the bone remodeling or gingival remodeling processes), but rather to enable researchers to learn from existing data and current tech-

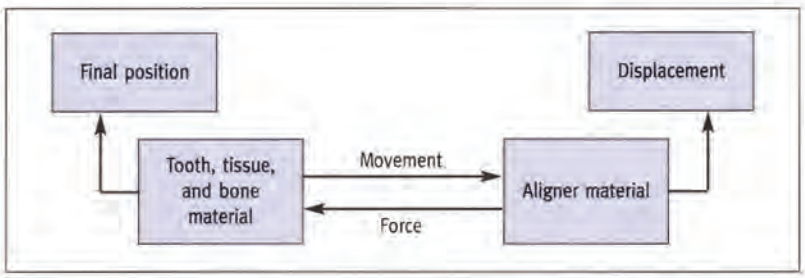


FIG 18-1 Conceptual model of the aligner-dental system.

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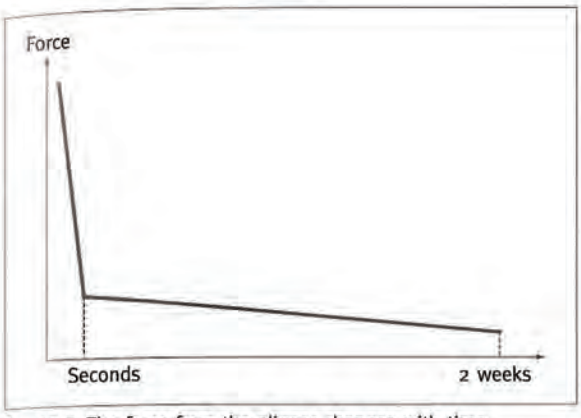


FIG 18-2 The force from the aligner changes with time.

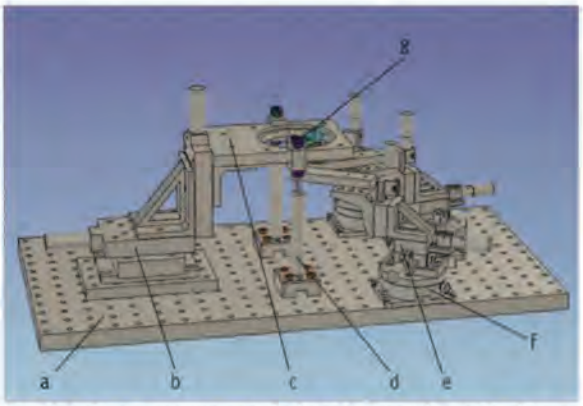


FIG 18-3 Force measurement device. (a) Board in which all components are attached; (b) translation table that holds the platform; (c) platform where the tooth models are fixed; (d) support structures that add rigidity to the platform; (e) translation table connected to the force gauge (sensor), which moves the sensor in x, y, and z directions; (f) rotation table fixed on the board and connected to the translation table (rotates along an upright axis); (g) force gauge (sensor).

nology. A secondary goal was to validate the methodology of the tooth movement model as a basis for future force studies. This model is based on previously established models of force measurements for tooth movement.

Finite Element Analysis Model

Developed in the late 1940s, finite element analysis is a technique created to help aerospace engineers design aircraft structures. Through the application of computer technology, FEA became useful as a tool for a variety of other engineering tasks. This technique is based on the premise that an approximate solution to any complex engineering problem can be reached by dividing the problem into smaller and more manageable (finite) elements. Using finite elements, complex partial differential equations that describe the behavior of certain structures can be reduced to a set of linear equations that can be easily solved using standard matrix algebra. FEA is used in a variety of engineering disciplines and also in dental and medical research.

With fast-advancing computer technology, FEA is now extensively applied in biomechanics to study the effects of forces on biologic systems. This method was used to simulate the force-displacement interaction between the dentition and the aligner. With this model, researchers can collect data on force distribution on the teeth and aligner surface consequent to a given displacement. The variability and complexity of tooth geometry and surrounding biologic tissue material, however, make simulation of the dental-aligner interaction extremely difficult. Additionally, tooth geometry and tissue properties vary from individual to individual and also from tooth to tooth within the same person.

Stresses That Develop in the Aligner During Thermoforming

FEA was used to predict the stress and strain on aligners and to estimate the final result of orthodontic movement using the tooth-movement model. Aligners are made from a 0.030-mil polyurethane material called Ex30. The blank material is made from a 5 × 5–inch sheet that is thermopressed over a stereolithographic (SLA) model of the teeth. Following thermal heating, the aligners are peeled off the model, trimmed, polished, and disinfected. In the thermoforming process, residual stress can be introduced into the material. The residual stress can change the mechanical behavior of the aligners and affect the force response under displacement, fatigue, and stress relaxation.

Although experimental data are available for the stress-strain relationship of Ex30 samples, no data are available on the stress-strain relationship of Ex30 once the aligners are formed over the tooth models. The complexity of the aligner geometry makes testing more difficult than for a flat single piece of material; however, using FEA it is possible to simulate how the material will react in the shape of an aligner.

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FIG 18-4 Cutout jaw with disk in STL format.



FIG 18-5 SLA model built from the STL model in Fig 18-4.

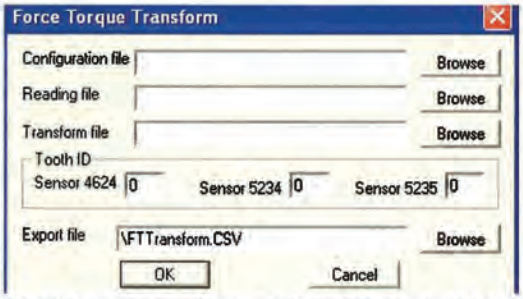


FIG 18-6 Interface of force transformation plug-in in Treat.

Forces Generated by the Aligner

The force response of an aligner under displacement depends on both the material properties and the geometry of the aligner. Material properties can be obtained by running material characterization tests such as tensile, compressive, and indentation tests. When the material properties are kept constant, the variation of geometry of the aligner affects the response to displacement. For example, changes in the thickness of the aligners produce different force responses to the same displacement.

It is difficult to measure the force response of an aligner directly on each tooth of a jaw. For one, the force gauges currently available are too big for this purpose. Second, the aligner contacts the tooth with the inner surface area and not the outer surface area, which creates further difficulty. Currently, there are no sensors that can monitor the pressure field in real time and fit between the aligner and the teeth. Third, because of the variability of the geometry of the teeth and the various malocclusions, the measurement device has to have various degrees of freedom to fit into the different geometries. Once the aligners are placed on the models, the problem of rigidly fixing the system arises. The difficulties with this, and how it affects the measurements, are discussed later in this chapter.

Force Measurement Device

To measure the force response of an aligner with a certain displacement, a special force measurement device was developed (Fig 18-3). Treatment is arranged into a series of stages. At each stage, only a small movement is designed and achieved. The force measurement device can be used to measure force vectors and torque vectors in the x, y, and z directions on three adjacent target teeth at each stage.

The fundamental design first requires creation of stereolithography (STL) files for the models on which measurements will be made; Fig 18-4 shows the STL file in Treat software. Subsequently, an SLA model is built based on the computer file. Figure 18-5 shows the SLA model built from the STL file shown in Fig 18-4. The aligners are then made from those SLA models using the thermoforming machine (see chapter 3).

The next steps in the process are to set up the force measurement device, which includes bonding target teeth, setting up data acquisition software, and initializing target teeth to their original position with respect to the reference jaw model at stage n. After this, measurements at stage n + 1 are made. Finally, vectors from the sensor coordinate are transformed to tooth coordinate systems. Figure 18-6 shows the interface of the Treat plug-in that performs the transformation.

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FIG 18-7 Model of measurement jaw and target teeth.

TABLE 18-1 Stiffness of aligner on teeth at room temperature and humidity*

	Translation (K)	
Tooth†	Kx (N/mm, 100 g/mm)	Kz (N/mm, 100 g/mm)
Central incisor	19.78	51.06
Lateral incisor	30.38	52.28
Canine	25.64	85.5
First premolar	16.02	28.38
Second premolar	15.82	43.42
First molar	16.95	33.9

*The values listed are much higher than what is normally expected in treatment protocols.
†All teeth tested were in the maxillary left quadrant.

To measure the force, a stage 0 model—which shows the initial position of the teeth—is used. The target tooth is then moved along the translation table along a certain direction. The tooth movement is recorded by the micrometer on the translation table (Fig 18-7).

From the experimental data it was found that when a single tooth is moved, a simple single force on the target tooth is not generated. Instead, forces on the adjacent teeth are also generated. In physics, this opposite and reactive force is known as *Newton's third law of motion.* Indeed, programmed movements on one tooth produce a force on other teeth as well. This principle also holds for fixed appliances and is well-known. When more than one tooth is moved, all these forces are simultaneously active. Some of the forces are additive, whereas others counteract each other. Because of this principle, it is extremely difficult to get a clear idea of the total force and direction. If the problem is examined through FEA, however, it is possible to develop a clear picture of what happened on the continuum of the aligner.

Stiffness of the Aligner

Aligner stiffness is the ratio of force to displacement along a certain direction on the aligner. The force measurement on initial tooth movement was performed using the device described above.

A central target tooth, which can be any tooth in the arch, is moved through adjustments made to the translation table connected to it. The total translation for each central target tooth is 1.25 mm, which is divided into 10 steps when turning the micrometer on the translation table. Only the translations along the x (buccolingual) and z (occlusal) directions were done because the flexibility of the measurement device in the y (mesiodistal) direction was too high to sustain loading. Table 18-1 presents stiffness data for several teeth. Further study is needed to determine the coefficient to convert the stiffness to those under body temperature and humidity.

Variation in Thickness of Gingiva

It is easy to understand that changing the aligner thickness changes the stiffness and therefore transmits different amounts of force. One of the factors that affects the thickness of the aligner is the height of the virtual gingiva, which is defined as the vertical distance between the lowest point on the frontal gingival line and the bottom of the gingiva in the Treat software. To test this postulate, an experiment was designed in which two groups of 10 aligners were made based on two SLA models. Aligners from both SLA models were identical except for the height of the virtual gingiva—which was twice as high in the second group (Fig 18-8). Once made from the SLA models, the aligners were weighed on a precision scale. Because the aligners were trimmed along the gingival line, which was the same for both SLA models, the surfaces of the aligners from both groups were considered the same. Therefore, the ratio between different weights of aligners is equivalent to the ratio of thickness. The study found that increasing the gingival height of the SLA model causes a reduction in aligner thickness. The mean weight of aligners with a 4-mm gingival height was 1.630 g (±0.036), and those with an 8-mm gingival height weighed 1.531 g

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FIG 18-8 Height (H) of gingiva used in two experimental groups.



FIG 18-9 Interproximal contact.

(±0.055). In addition, the two groups of aligners were used to measure the force response to the same displacement. One measurement was taken for each aligner in each group. The mean force is summarized in Table 18-2. As Table 18-2 shows, aligners formed on SLA models with higher gingiva generated less force, given the same displacement on the target teeth. Therefore, aligners built on higher gingival models have lower stiffness values.

Variation of Force Measurement

A study was designed to assess whether the variation in force measurement on different cases and setups could be estimated. If there is an error in estimation, what is it? The force measurement was grouped into different setups, which focused on various factors that might affect the variation of measurement. These factors are interproximal contact, complexity of tooth geometry, attachment, movement, and aligner thickness.

Where does the variation in force measurement results come from? First, variation exists in the aligners. No two aligners are identical, even if they were made for the same dental arch. Second, when an aligner is placed on the arch, its engagement is important. One aligner can be engaged on teeth slightly differently every time; that difference causes different force readings each time. Third, the target teeth do not occupy the same position in every trial—in other words, the device does not fit the target teeth position perfectly. The frictional contact between two adjacent target teeth can prevent them from returning to their original position after the position is disturbed by removing the aligner from the arch. Additionally, creep in the aligner contributes to measurement variations. After the aligner has been in place on an arch for some time, the aligner material loses its original strength, which results in the application of less force on the teeth. After the aligner is removed, the aligner material recovers its strength partially, depending on how long it was worn and how long it rests.



FIG 18-10 Bullet teeth on arch form with disk.

TABLE 18-2 Force (N) from aligners formed on SLA models with different gingival heights

	Sensors		
Gingival height	No. 4624	No. 5234	No. 5235
8 mm	1.68	2.22	1.25
4 mm	2.20	3.35	2.58

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Table 18-3 Force reading (F) on three target teeth* with interproximal contact

	Fx (N)	Fy (N)	Fz (N)
Sensor no. 4624			
SD	0.22	0.16	0.17
Mean	1.08	0.29	0.22
Sensor no. 5234			
SD	0.46	0.26	0.36
Mean	1.78	−0.30	0.28
Sensor no. 5235			
SD	**0.26**	0.27	0.17
Mean	**0.60**	−0.88	−0.35

**Sensor nos. 4624, 5234, and 5235 refer to the sensor series numbers connected to the target teeth.*

Table 18-4 Force reading (F) on three target teeth* without interproximal contact

	Fx (N)	Fy (N)	Fz (N)
Sensor no. 4624			
SD	0.34	0.26	0.10
Mean	1.04	0.10	0.28
Sensor no. 5234			
SD	0.57	0.14	0.20
Mean	1.87	−0.33	0.40
Sensor no. 5235			
SD	0.30	0.31	0.32
Mean	0.51	−0.76	−0.10

**Sensor nos. 4624, 5234, and 5235 refer to the sensor series numbers connected to the target teeth.*

In the following experiment, 10 aligners were made on one model for each testing purpose to alleviate the creeping effect. In every trial, a different aligner was used. If the measurement involved 20 trials, different aligners were used for the first 10 trials and then recycled from the first aligner for the next 10 trials. These data are presented in Tables 18-3 to 18-10.

Interproximal contacts

One SLA model was built with an interproximal contact (Fig 18-9). Ten aligners were formed on this SLA model. With the interproximal contact, force measurements were taken 10 times, each time using different aligners. The interproximal contacts between the target teeth were then removed mechanically using a diamond strip. The same 10 aligners were used to take measurements without the interproximal contact. Test of equivalent variance and Wilcoxon signed rank test were made between these groups to determine if they had equivalent variance. As presented in Tables 18-3 and 18-4, the data showed that the variance of the two groups was equivalent, which indicates that the interproximal contact does not contribute to the variation of measurement results.

Complexity of tooth geometry

Tooth geometry refers to the surface and curvature of the tooth. The variability in the geometry of a tooth is infinitely more complex than the geometry of any man-made mechanical part. Thus, if a tooth is thought of as a bullet that is aligned along the arch form, the tooth and arch geometry are substantially simplified (Fig 18-10). When an attachment is added, however, tooth geometry becomes more complex.

An experiment was conducted to examine the difference between a tooth in a bullet arch and a tooth in a typodont. In each testing arch, only the center target tooth

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TABLE 18-5 Force measurement (F) on bullet tooth arch

	Fx (N)	Fy (N)	Fz (N)
Mean	4.03	0.42	1.03
SD	0.72	0.38	0.38
S/M*	0.18	0.90	0.37

**(S/M) Ratio of standard deviation to mean force.*

TABLE 18-6 Force measurement (F) on the typodont arch

	Fx (N)	Fy (N)	Fz (N)
Mean	4.25	0.24	0.53
SD	0.94	0.47	2.51
S/M*	0.22	1.96	4.75

**(S/M) Ratio of standard deviation to mean force.*

TABLE 18-7 Force measurement (F) on the typodont arch with attachment on the target tooth

	Fx (N)	Fy (N)	Fz (N)
Mean	1.99	0.15	1.59
SD	0.39	0.25	1.28
S/M*	0.20	1.67	0.81

**(S/M) Ratio of standard deviation to mean force.*

TABLE 18-8 Force measurement (F) on target tooth with rotation along z-axis

	Fx (N)	Fy (N)	Fz (N)
Mean	−1.32	−0.53	−2.04
SD	0.42	0.56	2.50
S/M*	−0.31	−1.07	−1.22

**(S/M) Ratio of standard deviation to mean force.*

TABLE 18-9 Force measurement (F) on target tooth with rotation along y-axis

	Fx (N)	Fy (N)	Fz (N)
Mean	−1.69	−0.30	1.83
SD	0.44	0.48	0.86
S/M*	−0.26	−1.57	0.47

**(S/M) Ratio of standard deviation to mean force.*

TABLE 18-9 Force measurement (F) on target tooth with translation along x-axis

	Fx (N)	Fy (N)	Fz (N)
Mean	−4.25	0.24	−0.53
SD	0.94	0.47	2.51
S/M*	−0.22	1.96	−4.75

**(S/M) Ratio of standard deviation to mean force.*

had the same amount of movement, along the buccal and lingual directions. Measurements from 20 consecutive trials were made. The mean and standard deviations of forces were then calculated on the center target tooth (Tables 18-5 to 18-7).

Standard deviation to mean (S/M) is the ratio of standard deviation to mean force reading, which indicates how consistent the data are within each category. The smaller the ratio, the more consistent the data. For example, the comparison of S/M of Fx in Tables 18-5 and 18-6 indicates that the force measurement on the bullet arch is more consistent than that on the typodont arch. In the Force Measurement Device section, we mentioned the force transformation plug-in that can transform the force measurement from the force gauge coordinate system to the tooth coordinate system. The force gauge coordinate system is fixed on the force gauge itself, and the force gauge coordinate system consists of x-, y-, and z-axes, a typical coordinate triad. The tooth coordinate system is also composed of x-, y-, and z-axes. The x direction is the buccolingual direction; the y direction is the mesiodistal direction; and the z direction is the extrusion-intrusion direction. Therefore, each tooth has its own coordinate system. The data are presented to show how the repeatability of the data and variance compare between the data groups.

Theoretically, the addition of an attachment and consequent increase in the geometry of the tooth would produce an increase in the variation of the measurements. Interestingly, however, a comparison of Tables 18-6 and 18-7 shows that the addition of an attachment did not increase the variability of the results. Although the addition of an attachment increased the complexity of the geometry, it also introduced a good grip on the aligner, which helped to snap the aligner in a repeatable way. This

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might explain why the measurement results were contradictory to expectations.

Movement

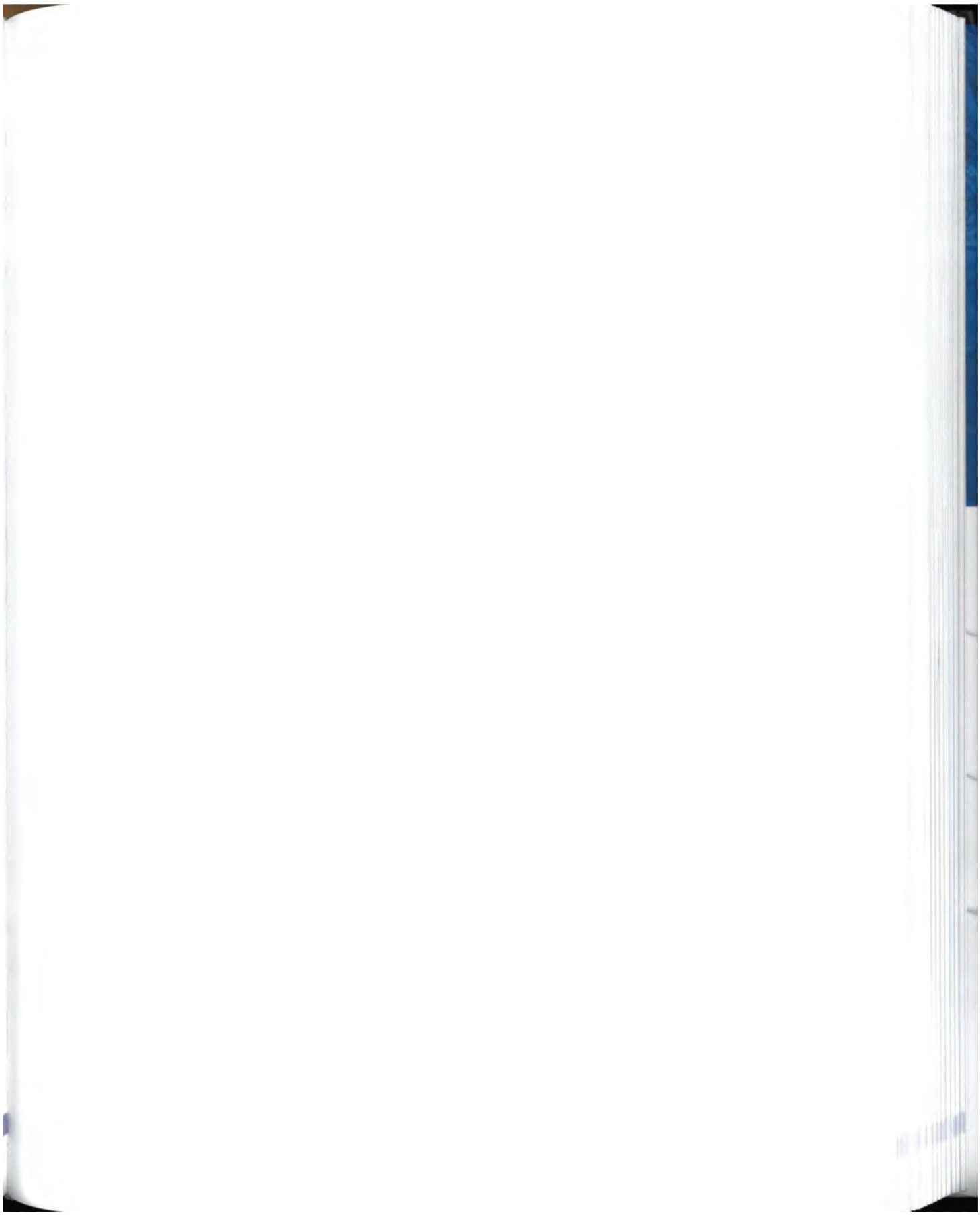
When the movement on a target tooth is rotation or translation, the rotation is carried by the aligner shape. Each time an aligner is placed on the jaw manually, the aligner position on the jaw slightly changes. This contributes to the variation in the force reading. Because rotation requires engagement of the tooth and the aligner, measurements for rotation showed higher variation compared to translation (Tables 18-8 to 18-10).

Summary and Future Studies

This chapter introduced the initial steps of studying the mechanics of tooth movement with the Invisalign appliance. The core of tooth mechanics research is the tooth movement model and the aligner FEA model. Generally, many techniques and methods in mechanical engineering have been and will continue to be applied to dental systems. The force measurement device serves as a workbench to validate the aligner FEA model. Once the aligner FEA model is developed, more tests can be performed to develop a better understanding of how the aligner moves the tooth and to optimize the aligner design.

Future studies are focused on the development and perfection of devices to measure the movement and forces generated with aligners. The first step is to improve the force measurement device to make the readings more consistent and accurate. The second is the development of FEA modeling of the aligner to better understand the forces generated with aligners. Last, our vision is to develop tooth movement models using the aligner to understand the effects of periodontal response under these forces.

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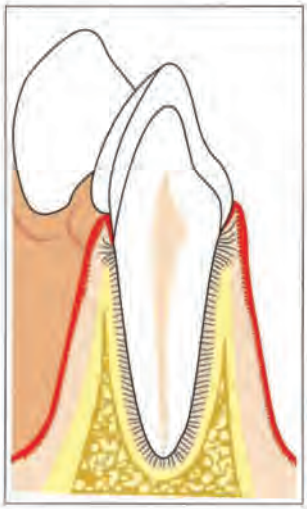


chapter 19

BIOLOGIC ELEMENTS OF TOOTH MOVEMENT

by
Orhan C. Tuncay, DMD

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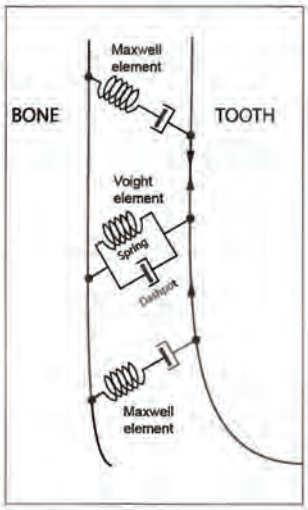


FIG 19-1 (*left*) Anatomy of periodontal support. (Modified from Lindhe et al[3] with permission.)

FIG 19-2 (*right*) Maxwell and Voight elements alternate between live and dead forms upon force application and its removal. These spring and dashpot parallel and serial configurations explain the viscoelastic properties of periodontal ligament upon loading.

Tooth movement is a product of periodontal remodeling that occurs as a result of an applied mechanical force. The origin of the mechanical force is irrelevant. When the mechanical force is exerted by a stomatognathic system applied to move teeth into a desired alignment, it is termed *orthodontic tooth movement*. In the absence of an orthodontic goal, however, such factors as occlusal force, habits, and posture can all move teeth, sometimes into a state of pathology.

It has long been suggested that orthodontic forces might damage the periodontium. It was first demonstrated in 1979 that extrinsic forces applied to move teeth elicit an inflammatory response from the periodontal tissues.[1] Typically, orthodontic forces create a wound deep in the periodontal tissues. The nature of this wound is hypoxia.[2] Recovery from this hypoxic condition in certain regions of the periodontal ligament (PDL) requires removal of bone. The inflammatory response is essential to bone remodeling. It can be argued that it is not the mechanical forces themselves that move teeth, but rather the remodeling of the periodontal tissue that creates the spaces into which teeth can be pushed by orthodontic appliances.

Understanding the clinical behavior of periodontal tissues is a prerequisite to the successful application of mechanical forces to move teeth efficiently and without undesirable sequelae. Our current knowledge of periodontal remodeling comes from experiments conducted to simulate fixed appliance effects: heavy forces, necrosis, a switch from normoxia to hypoxia or hyperoxia. These are the events that take place to heal the wounds created by the experimental orthodontic forces. In contrast, the biologic responses to Invisalign mechanics are different, as there is no periodontal wound to be healed.

Anatomy of Periodontal Structures Affected by Tooth Movement

The periodontal tissues have been defined as the "attachment apparatus," but they do more than hold the teeth in place. They are instrumental in determining tooth motility. The dentoalveolar structures, composed of teeth and the periodontium, are intrinsically dynamic structures. More important, however, the development of periodontal tissues is synchronous with the development of teeth. They are interdependent; one cannot exist without the other.

Gingiva

The masticatory mucosa includes the gingiva and the hard palate. The gingiva surrounds the teeth. Its final shape is determined by the position of the teeth during the growth and development of the oral structures. A fully developed gingiva can be categorized into three different sections (Fig 19-1). The region where the gingiva meets the tooth is known as the *free gingival margin*. Further apically, the tissue is called the *alveolar mucosa*. It is separated from the lining of adjacent oral structures by a demarcation zone called the *mucogingival junction*. Healthy gingiva is tightly attached to both the underlying bone and the tooth surface.

The gingival surface exposed to the oral cavity is keratinized. The keratin-producing cells are often devoid of

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nuclei. Additionally, the cells of this keratinized layer are tightly bound by a series of cytoplasmic processes called *desmosomes*. For purposes of orthodontic treatment, this tight bonding of gingival tissues is particularly significant in that it affects both the rate of tooth movement and the intra-arch stability of corrected tooth positions. Gingival remodeling is a significant factor in tooth movement.

Periodontal ligament

The PDL cuddles the tooth. It is composed of thick connective tissue and is highly vascularized. Its dependence on a constant blood supply is comparable to that of highly vascularized organs such as the heart and brain.[2] In addition to vascular cells, the PDL contains fibroblasts, osteoblasts, cementoblasts, osteoclasts, and epithelial cells. Nerve fibers are also present. Loose connective tissue fibroblasts present during development form the collagen fibers that attach to the cementum surface and the lamina dura of the alveolar bone. These fibers are classified according to their directional and positional arrangement: apical, oblique, horizontal, and alveolar crest fibers that go toward the crown.

The PDL space has an hourglass shape. It is narrowest at the midroot areas. The PDL width is approximately 0.25 mm (0.2 to 0.4 mm). Although narrow, it cushions the tooth when it is subjected to masticatory action or orthodontically generated mechanical forces. The viscoelastic properties of the PDL can be described by serial- or parallel-connected spring and dashpot elements[4] (Fig 19-2). Mechanical forces are selectively transmitted to the adjacent bone according to the duration and intensity of their initial application.

During periods of tooth movement, collagen fibers of the PDL are also affected. Normally, the collagen adjacent to the bone is less mature than the collagen next to the cementum. Thus, the collagen in the alveolar bone might remodel rapidly and the cemental surface fibers might not be affected at all. This arrangement may be responsible for the integrity of the PDL during orthodontic tooth movement.

Forces are transmitted to the tooth via the cementum layer. Cementum is a mineralized tissue that covers the root surface. It contains no blood or lymph vessels and is devoid of innervation. It serves to connect the tooth surface to the PDL; fibers attach to the cemental surface. Because the PDL does not have blood vessels, interruptions of the blood supply within the PDL are likely to affect cemental viability. This may be particularly true if the interruptions are sustained for a lengthy period.[5]

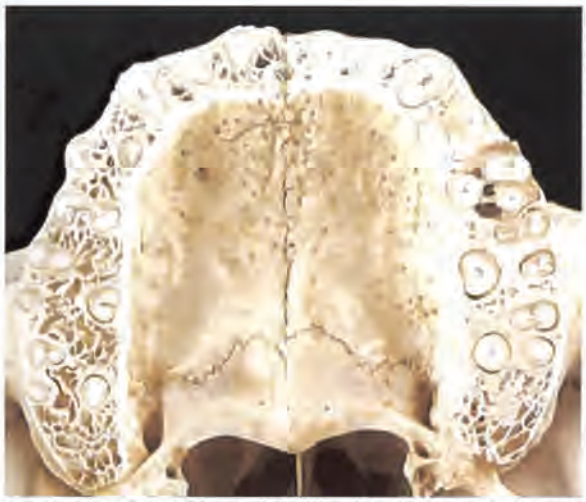


Fig 19-3 Basal bone is considerably wider in the posterior segments. Yet, the wider bone remodels more readily. (Reprinted from Lindhe et al[3] with permission.)

Alveolar bone

This special bone forms in response to the presence of the tooth. It is contiguous with the corpus maxilla and the mandible. The alveolar process develops in response to the formation and eruption of the teeth. Like all other bones in the body, alveolar bone has an outer layer of cortical bone and an inner trabecular structure. It is a thin band in the incisor region but thickens considerably around the molars (Fig 19-3). This design might relate to the forces these teeth will be subjected to throughout an individual's life. Oddly, alveolar bone is more readily remodeled around the posterior teeth than the anterior teeth.

The behavior of trabeculae has been studied extensively in orthopedics. Depictions of the load-bearing capacity and characteristic of the femoral head, for example, have been highly publicized (Figs 19-4a and 19-4b). In the alveolar bone, the response of trabecular structures (Fig 19-5) to orthodontic forces has not been investigated. It has been determined, however, that the alveolar trabeculae do not remodel—as had been theorized (Fig 19-6a and 19-6b).

Haversian canals form around the blood vessels. This structural characteristic might be linked to the calcification process.[6]

Osteoblasts are responsible for new bone modeling. These bone-forming cells densely populate the outer and inner lining membranes, the endosteum and periosteum, respectively. The alveolar bone is constantly remodeled as dictated by the functional demands placed on it (ie, the

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Fig 19-4a The femoral head section depicts the typical trabecular arrangement.

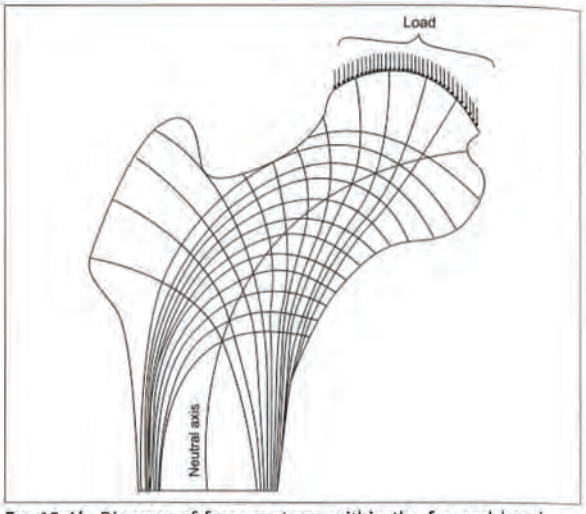


Fig 19-4b Diagram of force systems within the femoral head.



Fig 19-5 Alveolar bone trabeculae. Not much is known about their behavior during orthodontic tooth movement.

eruption or movement of teeth). The resorptive process is always associated with osteoclasts. During orthodontic tooth movement, the relationship between the lining membranes and the outer-layer tissues of the alveolar bone might be important. The tight connection of the gingiva to the periosteum could dictate the amount and rate of new bone deposition. Gingival tissue remodeling has been reported to be significant in tooth movement.[7] One could posit that the two determinants of alveolar bone remodeling during tooth movement are (1) gingival resistance to remodeling and (2) interruption of the vascular supply as a result of the squeezed PDL.

Blood supply

Gingival tissues receive their blood supply from various sources. This ensures uninterrupted nutrient supply despite the numerous insults intraoral tissues normally receive. It is interesting to note that the main vascular supply of the free gingiva from the supraperiosteal blood vessels anastomose with those from the alveolar bone and the PDL. Blood supply to the periodontal tissues is crucial: 50% of the PDL space, for example, is blood vessels by volume (Fig 19-7). Periodontal tissues receive their nutrient supply not only through the hydraulic force of arterial pressure but also through osmotic pressure. The difference between the two results in the transportation of substances from the blood vessels to and from the extravascular space.[3]

Periodontal Structures Subjected to Mechanical Forces

Perhaps alongside dental health, dental cosmetics has been in the minds of human beings since they first formed civilized societies. It was Aurelius Cornelius Celsus (25 BC to AD 50) of the Augustan age who wrote that finger pressure can move teeth into alignment.[8] Ever since, dental professionals have endeavored to find methods and implements for moving teeth into alignment that involve minimal effort, maximal comfort for the patient, and maximal efficiency.

The history of orthodontics is replete with the invention of novel appliances. It started with Edward H. Angle,

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FIG 19-6a Schematic arrangement of alveolar bone trabeculae at rest.

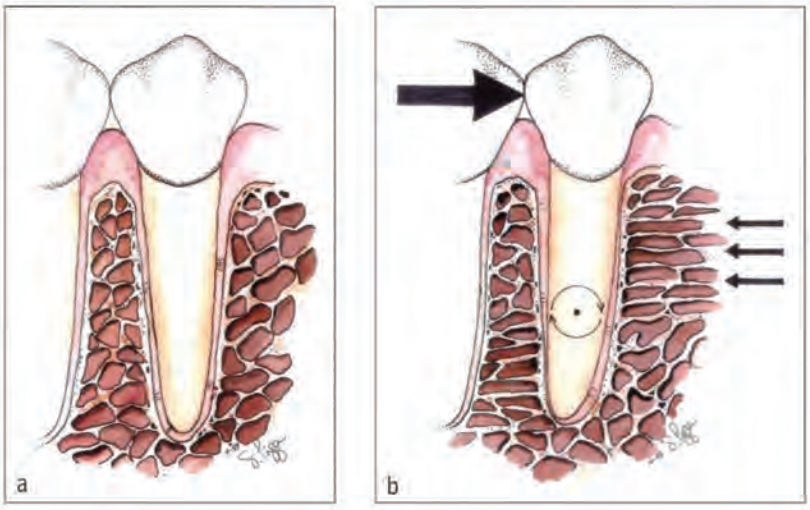


FIG 19-6b Theoretical rearrangement of alveolar trabeculae upon application of orthodontic forces (*large and small arrows*). Unfortunately, fractal analyses of radiographic images do not support the notion that these trabeculae rearrange to withstand the external forces maximally. *Circular arrows* represent the tipping direction of the tooth.

who was under contract with the SS White Company in Philadelphia to invent new appliances. Like today's novelists and musicians, who are under contract to regularly produce hit songs and best-selling novels, Angle was expected to deliver a regular stream of innovative orthodontic devices. Orthodontics, being the tradition-laden specialty that it is, has seen a multitude of appliances.

But it is clear that teeth are dumb.[9] They cannot distinguish the source of mechanical force. They move whenever and by whatever appliance applies pressure to them. This reaction is a complex process governed by the frequency, intensity, and duration of the applied force.

In earlier days, tooth movement in its most primitive form was explained as a pressure-tension hypothesis. That is, pressure causes resorption and tension deposition. Histologically, on one side of the root the PDL was compressed, and on the other side the fibers appeared to be stretched. Hence, the pressure-tension hypothesis was born. But evidence that compression causes resorption and that tension causes deposition does not exist. In the long bones, the opposite is true: pressure elicits deposition and tension elicits resorption. Even more fundamental than this debate, however, is the lack of evidence that mechanical forces applied to the teeth affect the bone at all. If this were the case, no implant would ever be successful. Indeed, one could apply significant force onto an implant, in various directions, and bone around the implant would not allow it to move. Ankylosed tooth is another example: it too will not move no matter how great a force is applied. Then what are the conditions that would cause the bone to remodel? Arguably, it has to be the soft tissues.[10]

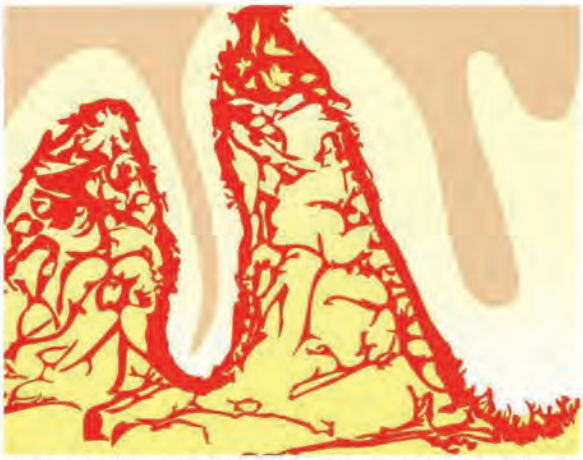


FIG 19-7 India ink perfusions have demonstrated that periodontal ligament is 50% blood vessels by volume.

Application of orthodontic forces results in subtle changes in the morphology and organization of periodontal tissues. It is known that in the initial stages of tooth movement, periodontal cells are compressed. It has been speculated that blood and extracellular fluid are forced from the periodontium into marrow spaces.[2,4,11] Escape of tissue fluids may lead to the creation of hypoxic regions or changes in tissue pH. Selective localized changes in the supply of blood to complex tissues such as alveolar bone and PDL cells are likely to produce profound changes in cellular metabolism. It has been suggested for 20 years that, in highly vascularized tissues, this type of change can result in increased dependence on glycolysis or inhi-

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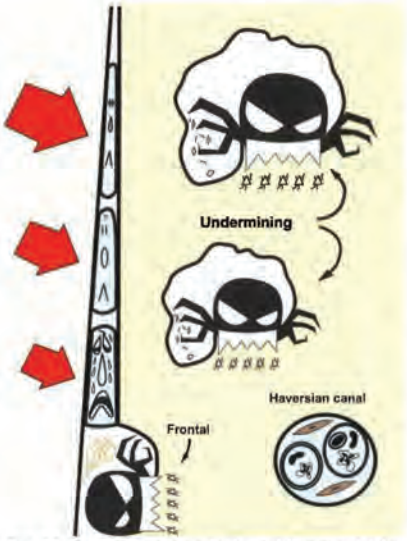


FIG 19-8 Squeezed periodontal ligament triggers undermining resorption in marrow spaces and frontal bone resorptive activities in socket walls.

bition of both glycolytic and respiratory activity.[12] In the dentoalveolar complex, these effects may vary according to the cells' need for oxygen and their ability to adapt to an environment of low oxygen tension.

Periodontal Ligament and Alveolar Bone Under Stress

The PDL forms a cushion around the root of the tooth. It is, therefore, the initial site affected by any mechanical force applied to the tooth. If the magnitude of the applied force exceeds the dampening capacity of the PDL, which is approximately similar to the arterial blood pressure, then the ligament is squeezed. The dampening capacity is determined not only by the cells, vascular elements, or collagen fibers that populate the ligament space, but also by the glycosaminoglycans that hold the interstitial water. Accordingly, both the magnitude and the duration of the applied force are important. High magnitude–low duration perturbations force the PDL to behave like a solid material. Sustained high-magnitude forces, on the other hand, elicit significant injury within the PDL in the form of necrosis. The necrotic tissue forms in response to the occluded blood vessels and the hypoxic condition that result. This necrotic tissue is eventually removed as newly formed blood vessels grow into the area. When teeth are moved

TABLE 19-1 Tooth movement achieved in felines with and without administration of inflammatory mediators

Treatment protocol	Tooth movement (mm)
NSAID	1.12
No medication	2.34

with fixed appliances, formation of a necrotic zone within the PDL is inevitable. In contrast, animal studies have shown that it is possible to apply sustained or intermittent forces of very low magnitude to elicit a remodeling response without inflicting injury. Tiny beads bonded onto premolar teeth have been shown to effect tooth movement simply through the pressures exerted on them from the cheek or the tongue.[13]

The injured PDL takes time to heal. Indeed, until the necrotic tissue is removed, the tooth does not move. While the healing takes place, alveolar bone reacts to the presence of the necrotic tissue with resorption in the marrow spaces. In time, as vascular activity removes the necrotic region, walls of the socket next to the compressed PDL are also resorbed. The first resorptive process is commonly known as *undermining resorption*, and the latter as *frontal resorption* (Fig 19-8). Eventually, these two resorptive regions connect to form the large space into which the tooth can move. Clearly, remodeling of the PDL under forces generated by fixed appliances is nothing more than a wound-healing process. Accordingly, conditions present in any kind of wound healing anywhere in the body are likely to occur in the periodontal tissues as well. In its simplest form, wound healing is an inflammatory response. Thus, mediators of inflammation need to be examined as they may affect the remodeling process. These mediators are also involved in the pain associated with tooth movement.

Most of our knowledge of periodontal remodeling comes from animal studies. Many of the published animal studies are done over a 14-day period. Unfortunately, the periodontal tissue complex is such that within the 14-day period just about anything could be "proven." Once the investigation is extended to 21 or 28 days, the differences in cellular activity or the rate of tooth movement seen earlier tend to disappear. Experimental designs that span over 3 to 4 weeks are technically difficult because of high attrition rates. Animals are hard on delicate orthodontic appliances. Long-duration experiments better differentiate the artifactual and real effects of the experimental variable.

It was first shown in 1980 that the rate of tooth movement is regulated by inflammatory mediators.[1] Administration of the aspirinlike drug indomethacin to laboratory

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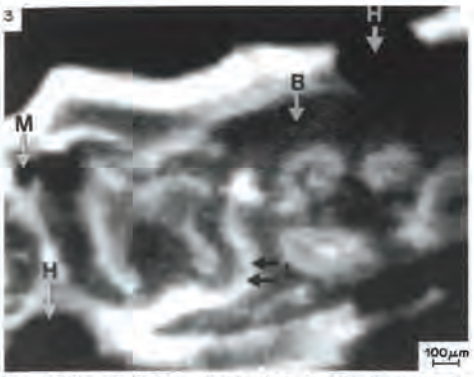


Fig 19-9a NAD/NADH distribution in the transversely sectioned rat maxillary dentoalveolar complex. (M) metallic marker; (B) bone; (H) hole; (L) periodontal ligament.

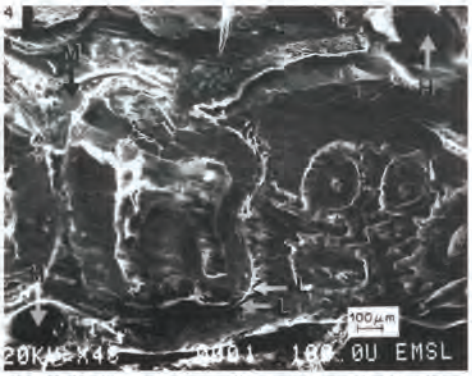


Fig 19-9b The corresponding anatomy for the fluorescence images above. (M) metallic marker; (H) hole; (L) periodontal ligament.

animals slowed the rate of tooth movement by 50%. Pooled measurements for tooth movements were 1.12 mm for felines that received indomethacin and 2.34 mm for those that received no medication (Table 19-1).

Indomethacin inhibits the synthesis of prostaglandins (PGs). This finding corroborated the suggestions pertinent to bone loss in inflammatory periodontal disease. Interestingly, patients with chronic arthritis who take aspirin daily exhibit less periodontal bone loss than age-matched controls, even if they are unable to maintain a regimen of good oral hygiene.[14] Direct injections of PGs into the dental papilla increase the rate of tooth movement, but because PGs are also pain mediators, patients experience significant pain. If teeth are not moving predictably, the experienced clinician will know to ask if the patient is on a daily aspirin regimen. All nonsteroidal anti-inflammatory drugs (NSAIDs) work the same way. In addition to these problems with NSAIDs, inhibitors of bone resorption such as biphosphonates (Fosamax) also slow the movement of teeth. Although these medications are known to inhibit tooth movement by affecting the remodeling process, they have not been explored for their potential to prevent relapse.

The orthodontist's inability to precisely control the force magnitude with fixed appliances necessitates a discussion of the metabolism of tissues subjected to extreme changes in blood supply. The energy status of the cells that make up a tissue or organ governs a wide range of metabolic, biosynthetic, and secretory functions. In a mixed structure, such as the dentoalveolar complex, measurement of energy metabolism by biochemical methods is a formidable challenge, as it is impossible to dissect and collect individual tissues without disturbing their metabolic status. It has been possible, however, to measure the metabolic state of the dentoalveolar structures using a technique called *microfluorimetry*.[6] The basis of this technique is that the mitochondrial oxidative activity is reflected in the redox status of the respiratory chain: areas of high oxidative activity within a given tissue contain low levels of nicotinamide adenine dinucleotide (NADH), whereas the tissues that are glycolytic have high NADH levels. Scanning microfluorimetry records the fluorescence of this reduced pyridine nucleotide. The data gathered with this technique reveal that the vascular structures such as the alveolar bone, the pulp, and the PDL exhibit a high oxidative state and the gingival tissues a low oxidative state (Figs 19-9a and 19-9b).

These findings do not differ in a scan from the apical to the coronal. But it was clearly shown that the PDL is hypoxia-sensitive, similar to the heart, kidney, and brain. Alveolar bone, on the other hand, appears to be more resistant to a reduction in oxygen supply. Thus, it can be suggested that during the course of orthodontic tooth movement (and possibly periodontal disease), changes in oxygen supply to discrete regions of the periodontium may trigger alterations in cellular energy metabolism and consequent remodeling. This point was further strengthened by the studies of nitric oxide (NO) synthesis in the PDL during tooth movement.[15]

Up until a decade ago, NO was considered merely an environmental pollutant. It was not until NO was recognized as an endothelial relaxing factor that its importance in biologic systems began to emerge.[16] Since then, evidence has revealed an involvement of NO in a wide array of key physiologic processes, including regulation of vascular tone, platelet aggregation, host defense, inflammation, neurotransmission, learning and memory, penile erec-

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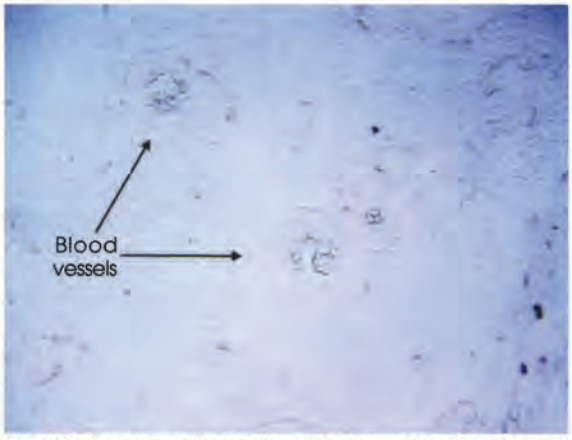


FIG 19-10a Immunochemically stained periodontal ligament blood vessels at rest (original magnification x100; immunohistochemical staining for anti-NOS). (Reprinted from Borgan et al[15] with permission.) .



FIG 19-10b Periodontal ligament blood vessels under strain. Note the intense NOS staining (original magnification x100; immunohistochemical staining for anti-NOS). (Reprinted from Borgan et al[15] with permission.)

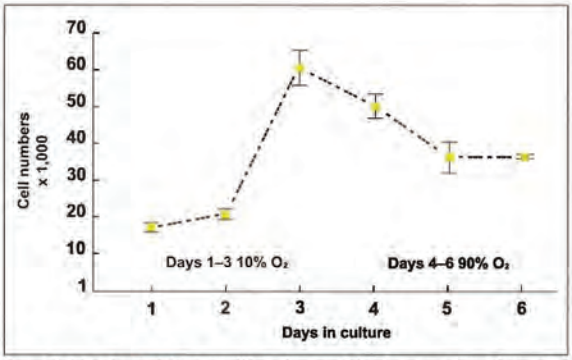


FIG 19-11a Osteoblast proliferative activity in crossover low and high O2 saturations in culture media.

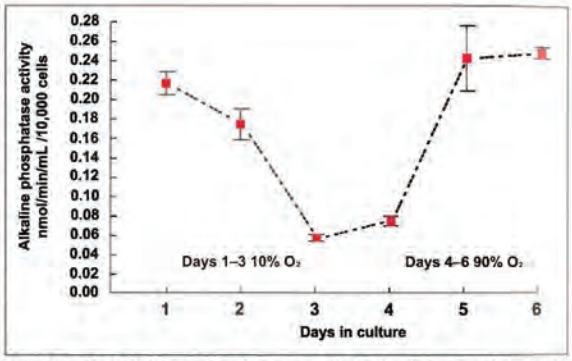


FIG 19-11b Alkaline phosphatase activity in the osteoblasts in low and high oxygen availability.

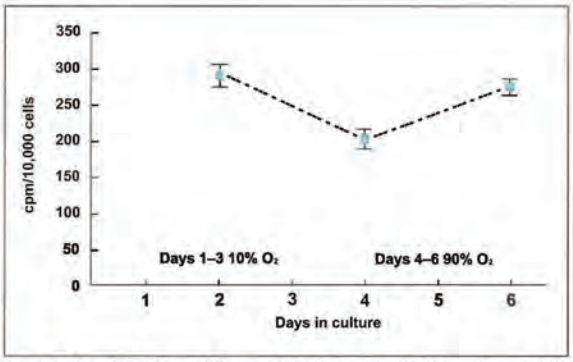


FIG 19-11c The effect of low and high oxygen in the culture medium on total collagen synthesis. (cpm) counts per minute.

tion, gastric emptying, hormone release, cell differentiation, cell migration, and apoptosis. Some of these processes have similarities to those that take place during tooth movement. The half-life of NO in a physiologic milieu is 1 to 10 seconds. It is difficult, therefore, to study NO production directly in an in vivo setting. An alternative is to study the localization of nitric oxide synthase (NOS) enzymes, which endogenously produce NO.

Studies to identify the sites of NOS activity in the periodontal tissues of stationary and orthodontically moved teeth have revealed significant differences. The periodontal tissues of stationary teeth exhibited hardly any immunohistochemical staining for NOS (Fig 19-10a). In contrast, NOS activity in the PDL blood vessel walls was strikingly increased in teeth that had undergone orthodontic tooth movement (Fig 19-10b). Even after the orthodon-

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FIG 19-12 Overgrown gingival tissues inhibit tooth movement.



FIG 19-13 Inflamed and fragile gingival tissues will offer very little resistance to tooth movement and will remodel readily.

tic appliance activity had decayed (in 28 days), NOS activity could still be detected in the connective tissues surrounding the roots. The NOS-stained tissues included the interradicular bone. These data strongly support the argument for the importance of vascular activity within the periodontal complex during orthodontic tooth movement.

Alveolar bone may not be as sensitive to oxygen availability as the brain, kidney, heart, or the PDL, but can it still be affected to some extent? There is significant evidence that bone growth and repair exhibit such dependence. The presence of an oxygen gradient in epiphyseal growth cartilages[6,17–19] or in fracture hematoma[20] has been shown to play a role in bone growth and repair. These observations have been supported by the report that chondrocytes of distinct maturational level (proliferating and calcifying) exhibit differences in oxygen consumption and in energy-charge ratio.[2] Furthermore, the initial foci of calcification are in intimate contact with blood vessels,[20] and the calcifying cells exhibit higher NADH/NAD ratios than do their counterparts that are more distant to the vascular canal.[21] In tooth movement, the compressed PDL blood is squeezed out, causing the vessels to collapse. On the tension side, however, they dilate. Eventually, collapsed vasculature is reestablished and the bone resorbed. The dilation of blood vessels on the tension side appears to be conducive to new bone deposition.[22,23] These reports indicate that the functional state of calcified tissue cells is intimately associated with vascular canals, and form the rationale for the hypothesis that during tooth movement alveolar bone remodeling is triggered by changes in oxygen availability.

The regulation of osteoblast function by oxygen tension has been studied in vitro.[24] In low ambient oxygen tension, cellular proliferation increases, whereas alkaline phosphate (AP) activity, collagen synthesis, and media partial pressures for oxygen and carbon dioxide (pO_2 and pCO_2, respectively) decrease. In contrast, hyperoxic conditions suppress cellular proliferation and produce concomitant increases in AP activity, collagen synthesis, and pO_2 and pCO_2. When the conditions are reversed—that is, when hypoxic cells were put in a hyperoxic environment—their metabolic activities were abruptly reversed. It was shown, therefore, that in the absence of humoral, intercellular, or tissue architectural considerations, oxygen availability can serve as a trigger for bone remodeling (Figs 19-11a to 19-11c).

Gingival Response to Tooth Movement

To the clinician, alveolar bone appears to be subject to the dictates of PDL vascular activity. But if bone is not critical, why do teeth move very slowly? The potential resistance of gingival tissues was explored.[7] When the gingiva was eliminated, teeth moved faster. If bone limited the rate of tooth movement, elimination of gingival tissue would not slow tooth movement. This finding does not come as a surprise to the expert clinician. It is nearly impossible to close an extraction site into which a gingival invagination has developed. The expert orthodontist always asks the oral surgeon to preserve the buccal cortical plate by not squeezing it as conventionally taught in dental schools. The positionally intact cortical plate prevents invagination.[25] The clinician cannot move the teeth to close residual spaces if gingival tissue is present. As with an invagi-

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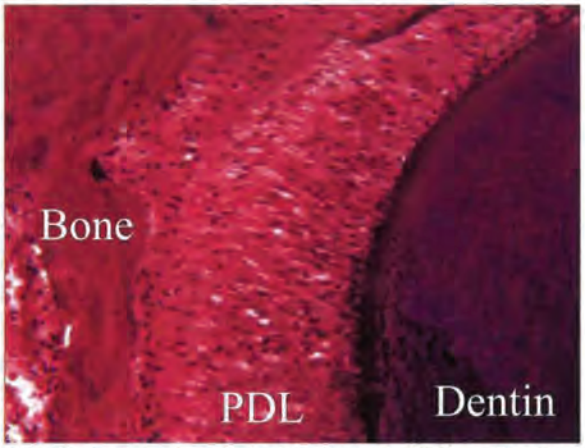


FIG 19-14a Normal periodontal ligament (PDL) architecture. (Reprinted from Nicozisis et al[29] with permission.)

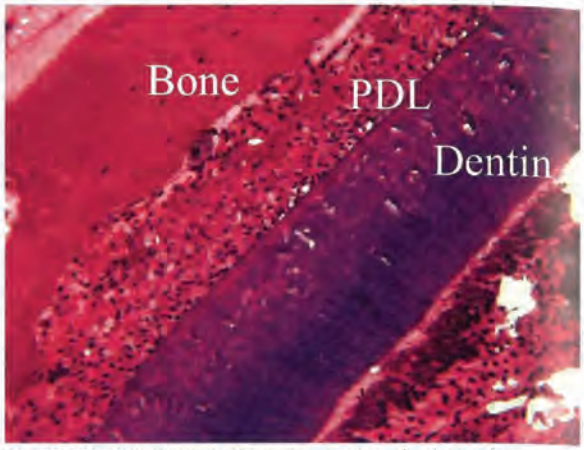


FIG 19-14b Relaxin-treated specimen. Note the loss of organization of periodontal ligament (PDL) fibers. (Reprinted from Nicozisis et al[29] with permission.)

nation, a true frenum diastema is nearly impossible to close unless it is eliminated by surgical dissection. Also known are the inhibitory effects of overgrown gingival tissues in patients taking medications such as Dilantin (phenytoin) or cyclosporine. Gingival overgrowth can also occur idiopathically; some patients react to the presence of fixed appliances with overgrowth (Fig 19-12). Both types of overgrown gingival tissues share one common characteristic: resistance to remodeling.

Resistance to remodeling may only be an issue with fixed appliance treatment. That is, matters such as diastema closure and gingival invagination do not generally occur when the teeth are moved with aligners. Aligners permit precise, controlled movement of teeth; the gingival tissue conforms to the gentle forces generated by the Invisalign System. The tissue contour looks excellent, exhibiting no signs of inflammation at the gingival margins. Since the gingival tissue does not contain any elastin (except in conjunction with the blood vessels), its remodeling rate appears to correlate well with the rate of tooth movement with an aligner.

In stark contrast, inflamed gingival tissue is fragile and loose, offering little resistance to tooth movement (Fig 19-13). In such cases, the orthodontist knows the teeth can be moved quickly and the treatment brought to an end. Of course, the combined effect of inflamed gingiva and mechanical force could cause a reduction in crestal bone height. Nonetheless, in this scenario the only determinant of tooth movement is the degree and depth of injury inflicted by the fixed orthodontic appliance. In practical terms, tooth movement rate in such conditions is determined by the rate of alveolar bone remodeling. Theoretically, the alveolar bone remodels more efficiently if the PDL is not injured and the formation of necrotic areas is avoided.

To summarize, efficient tooth movement can be achieved if the following conditions are met: (*1*) the periodontal ligament is not necrosed, (*2*) the gingival tissues offer no resistance, and (*3*) the vascular activity is abundant.

The first condition can be met if orthodontic force does not squeeze the PDL more than its thickness. Teeth move with the slightest of sustained forces; the Invisalign System is designed to apply such a force. With the Invisalign System, tooth movements are highly controlled and incremented as in the ClinCheck. In an effort to increase vascular activity noninvasively, ultrasound is applied to the gingival tissues of the orthodontically moving teeth. Ultrasound has been shown in rabbit models to accelerate the healing of fractured bones by increasing vascular activity. Mechanical forces (specifically, tooth brushing and orthodontic tooth movement) have been shown to affect gingival blood flow.[26,27] Unfortunately, clinically applied ultrasound has not been shown to yield faster tooth movement.[28] Although mechanical perturbation did not influence the rate of tooth movement, hope for a physiologic adjunct persists. Indeed, how the hormone relaxin might modulate the remodeling of the periodontal connective tissue has been investigated in an exploratory study.[29]

Relaxin is produced by pregnant females. It relaxes the pubic symphysis to widen the birth canal for parturition.

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Clinically, relaxin has been tested as a possible treatment for scleroderma, but it also exerts effects on other parts of the body—especially the joints, ligaments, and regions containing collagen and fibroblastic activity. For example, temporomandibular joint (TMJ) problems disproportionately afflict female patients. A role of the female reproductive hormones has been proposed in the onset and progression of these diseases, but no direct evidence links female reproductive hormones to TMJ disorders. Relaxin alone, or in combination with beta-estradiol, has been implicated in the degradative remodeling of the fibrocartilaginous disc.[30]

It was shown in organ culture that the suturelike structures (cranial sutures or the PDL) possess receptors to relaxin. Interestingly, these receptors are also present in males. Addition of relaxin to the culture medium resulted in explicit changes in the collagen fibril arrangement of the PDL: from being dense and highly organized with a perpendicular direction between tooth and bone to randomly organized, loose, and devoid of any directionality between the tooth and bone (Figs 19-14a and 19-14b). Additionally, protease activity was increased in the relaxin-treated cultures.[29] In recent years, several studies have provided increasing evidence that relaxin can also act on several of its targets by increasing the expression and activity of NOS isoenzymes, thereby promoting the generation of NO.[31]

The future is exciting, as a switch from Platonic thought to Hippocratic is within our grasp.[32] If tissue behavior could be modulated (as opposed to building different and smaller brackets), orthodontics will truly become a biology-based field of study and practice. Invisalign provides the element of controlled force application, but it is the hope that the gingival tissue compliance will be enhanced by a routine topical application of relaxin.

Cementum

Cementum is a mostly acellular layer that covers the root. Only around the apex can a cellular cementum be seen. The PDL connects to the tooth via the cemental layer. Cementum is not directly involved in determining the rate of tooth movement; nevertheless, cementum is a source of concern to the clinician because it often resorbs during tooth movement, taking the dentinal portion of the root with it. Indeed, orthodontic treatment is known to be the most common cause of apical root resorption. Factors responsible for external apical root resorption (EARR) are not well understood. Clearly, these factors can be patient- or treatment-related. It was recently reported that variations in the interleukin (IL)-1β allele 1 cytokine is strongly associated with an increased risk of EARR.[33] Patients homozygous for IL-1β allele 1 have a 95% chance of developing root resorption greater than 2 mm. Clearly, individual susceptibility cannot be predicted by the methods commonly available to the practitioner today.

Treatment-related mechanics, however, can be controlled. It is essential to understand these mechanic-related factors. Unfortunately, the published literature is not uniform and well controlled. Most of our knowledge of the mechanisms of root resorption comes from animal studies, which are of limited clinical utility because of limitations related to their design. Usually, animal studies examine short-term experimental conditions with the significant magnification of scanning electron microscopy and report seemingly significant conclusions. Undoubtedly, such conclusions are scientifically accurate, but actual clinical shortening of the root is rarely the experimental condition. Thus, we are perplexed to explain the treatment-related elements of EARR. These can be the frequency and magnitude of force application, duration of each force or overall treatment, or the direction in which these forces are applied. Whether orthodontically induced root resorption is a factor or not, the maxillary central incisor resorbs more than any other tooth during the course of orthodontic treatment.[33–35] The characteristics of the supporting bone may also be a factor. It has been postulated that tooth movement in dense bone requires greater or longer force application and consequently results in more root resorption.[27] In a rodent model, teeth were shown to move faster and develop EARR in animals that had a calcium-deficiency–induced decrease in bone density.[36] Similar experiments in dogs also showed slower tooth movement in denser dentoalveolar complexes.[37] Proximity of the root to the cortical bone has been suggested as a potential factor, but this could never be proven. A recent study could not demonstrate that the density and morphology of the dentoalveolar complex were significant factors in the etiology of EARR.[38]

A meta-analysis of treatment-related factors considered the distance the apex of the maxillary central had moved.[5] Total apical displacement might represent a better marker for overall treatment duration. Also, there is no way to move a maxillary apex any considerable distance using fixed appliances without forming extensive necrotic regions with-

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in the PDL. Perhaps this is why the maxillary centrals resorb the most. The meta-analysis revealed that root resorption was strongly correlated with total apical displacement and the time it took for the apex to traverse the distance. Thus, it can be concluded that in predisposed individuals distance is critical. Greater distances take longer and create extended regions of hypoxia within the PDL, which could ultimately affect the cemental layer.

But how important is root resorption for the health of the tooth? Severe root resorption is distressing to the orthodontist. When confronted with root resorption, at what point should the treatment be terminated? The perceived significance of root resorption may, in fact, be overstated. Only minor inconveniences have been suggested even in the most severe cases of resorption. There have never been any reports of iatrogenic tooth loss as a result of severe orthodontic root resorption. The worst outcome has been hypermobility.[39]

The amount of periodontal attachment loss following root resorption has been computed in a theoretical model.[40] Results indicated that 4 mm of root resorption translates to 20% total attachment loss and that 3 mm of apical root loss equals only 1 mm of crestal bone loss. After the initial 2-mm apical root loss, calculations revealed that every additional 2-mm root loss equaled only 1 mm of crestal bone loss.

The seriousness of dentists' perception was reported[41]; the reaction of general practitioners (GPs) and different specialty groups to morphed images of 10% to 50% root resorption was widely varied. GPs were the most concerned about root resorption. Although most practitioners believe that 50% root resorption is significant and detrimental to the longevity of the tooth, extraction followed by prosthetic replacement was never viewed as a viable option. There was no agreement among practitioners as to when orthodontic treatment should be terminated. Overall, GPs were the most conservative, suggesting termination after 35% root loss. History of trauma, genetic disposition, and root morphology are the most cited predisposing factors. Lengthy treatment times were of greater concern to GPs than to orthodontists. With the exception of orthodontists, dentists believe excessive force is detrimental to the root, but no one is able to define what excessive force is. Overall, dental school curricula overstate the causes of root resorption. This study suggested that many dental professionals base their opinions on myths and are largely inconsistent in their assessments.

Summary

Our current understanding of mechanical force effects on the periodontal tissues comes from experiments that simulate fixed appliance therapies. Thus, for more than a century, we have had studies of the effects of rather heavy forces. From the discussions in this chapter, it can be concluded that fixed appliances inflict serious injury to the supporting periodontal tissues. An increased blood supply—but not as a result of wound healing—is important for the maintenance of tissue integrity and the promotion of accelerated tooth movement. Activations of the orthodontic appliance in increments of the width of the PDL are best.

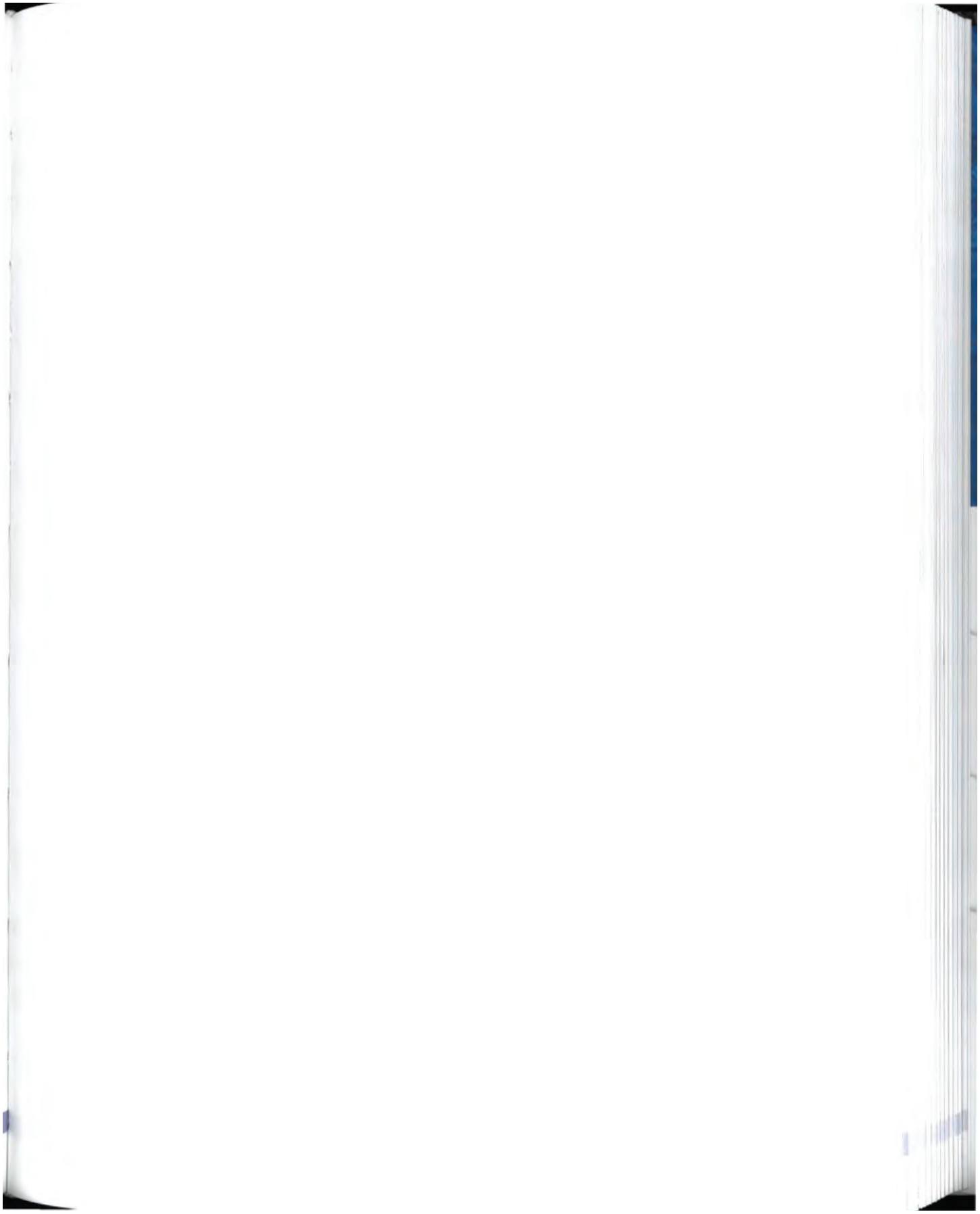
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chapter 20

PROPERTIES OF ALIGNER MATERIAL EX30

by
Robert Tricca, PhD and Chunha Li, PhD

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A survey of the literature indicates that a multitude of materials has been used throughout the history of dentistry. The role of biomaterials in orthodontics was reviewed comprehensively by Kusy.[1] Indeed, the use of biomaterials in dentistry dates back to the Etruscans (100 to 400 bc), who fashioned dental space retainers from gold bands and calves' teeth. Pierre Fauchard (1678–1761), a French surgeon considered by many to be the "Father of Orthodontics," worked with gold and silver while developing orthodontic appliances such as the bandolet, an appliance designed to expand the dental arch. In the late 1800s and early 1900s, a plethora of materials became available for the fabrication of orthodontic appliances (ie, loops, ligatures, spurs—including platinum, stainless steel, gum rubber, vulcanite, and various metal alloys such as brass). Occasionally, wood, ivory, zinc, and copper were also used.

While the introduction of novel orthodontic materials slowed dramatically from the early 1930s through 1960, it was during this period that stainless steel gained in popularity as the wire material of choice, ultimately leading to the abandonment of the noble metal alloys by the 1960s. Stainless steel exhibited superior mechanical properties and outstanding corrosion resistance and was available at reasonable cost. More advanced materials emerged in the 1960s and 1970s. Cobalt-chromium alloys were introduced in the 1960s. Research efforts at the Naval Ordnance Laboratory led to the discovery of nitinol, an alloy of nickel and titanium, in 1962. Later generations of nickel-titanium (NiTi) alloys would feature superelasticity and shape-memory effects. Toward the end of the 1970s, meta-stable titanium alloys based on beta-stabilized titanium were introduced. The 1980s saw further diversification in orthodontic materials with the development of ceramic appliances.

More recently, a novel computer-aided design/computer-assisted manufacture (CAD/CAM) approach has been developed that utilizes a clear thermoplastic to accomplish orthodontic tooth movement. For the Invisalign System, a series of clear, plastic tooth-positioning devices, or aligners, are fabricated with programmed movements. The use of thermoplastic materials to facilitate tooth movement represents a significant departure from the past (except as noted in chapters 1 and 3) and present for the practicing orthodontist. While thermoplastics have the potential to offer distinct advantages (eg, clarity, removability, ease of use, etc), their chemistry presents challenges when used in the oral cavity. The aim of this chapter is to investigate the properties of thermoplastics, as well as the experimental techniques used for determining their applicability for use in the oral cavity.

An Overview of Thermoplastic Polymers

Thermoplastics are based on linear or slightly branched polymers, which have strong intramolecular covalent bonds and weak intermolecular van der Waals bonds. At elevated temperature, it is easy to "melt" these bonds and cause the molecular chains to flow over each other. During this process, the thermoplastic material does not undergo any chemical changes. When cooled, however, the molecular chains solidify into new shapes. The process of softening with heating and hardening may be repeated. One example of this is the recycling and reprocessing of thermoplastic scrap.

In their solid form, thermoplastic materials fall within two classes of molecular arrangement: amorphous or semicrystalline. At a microscopic level, the long polymer chains of amorphous thermoplastics are randomly ordered in space. Amorphous thermoplastics do not exhibit exact melting points (T_m). Yet, when heated to a characteristic temperature called the *glass transition temperature* (T_g), they become less brittle and more flexible. In contrast, the long polymer chains of crystalline thermoplastics tend to be packed together in an orderly way, similar to the way atoms are arranged in a metallic crystal. Crystalline thermoplastics exhibit well-defined melting points and glass transition temperatures. Some thermoplastic materials may contain crystalline and amorphous regions. An example of this is high-density polyethylene (HDPE), a hydrocarbon thermoplastic polymer that exhibits a well-defined melting point as well as a glass transition temperature.

Polymer crystallinity is a factor that has a significant influence over polymer properties. For instance, the degree of crystallinity determines if a polymer is opaque or transparent. Similarly, the presence of a well-defined glass transition temperature affects the ease with which a polymer may be thermoformed. Both of these material properties should be considered when evaluating thermoplastics for the Invisalign System.

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Properties of Aligner Materials

Mechanical properties

As an aligner is fitted on a patient's dentition, a force develops in areas with programmed tooth movement. The force results from the displacement of the aligner material; it is this force that causes tooth movement. Programmed tooth movements may vary from relatively simple movements (such as tipping of a tooth in one dimension) to more complex movements that involve bending motions coupled with rotational movements. The extent of aligner displacement and the resultant forces and moments produced on the teeth depend upon the movement programmed into the aligner, the material thickness, and the intrinsic material stiffness.

Aligners are subjected to both short-term and long-term loading forces. For example, an aligner is subjected to a short-term load when a patient fits an aligner on his or her teeth. Once fitted to teeth, aligners are subjected to intermittent long-term loads while being worn between meals and overnight. These longer-term loads are caused by programmed tooth movements and the biomechanical forces generated from the musculoskeletal system in the oral cavity.

A thermoplastic polymer is the structural material used in the fabrication of aligners. Understanding the mechanical properties of polymers is therefore critical if we are to assess the performance of a particular thermoplastic material as a means for accomplishing tooth movement. Mechanical properties may be investigated by studying how a material deforms when subjected to an applied force. By varying the nature of the deformation and the duration of the applied force, we can learn much about the mechanical properties of a thermoplastic.

Forces applied over a short duration

The generation of stress-strain curves is a useful approach in the evaluation of a material's mechanical properties. Numerically, stress in any direction at a given point in a material is simply the force or load that happens to act in that direction at that point divided by the area on which the force or load acts. If stress at a certain point is *s*, then

$$\text{Stress} = s = \text{load/area} = P/A$$

Similarly, strain is a measure of how far apart the atoms at any point in a solid are being pulled apart (ie, by what proportion the bonds between the atoms are stretched).

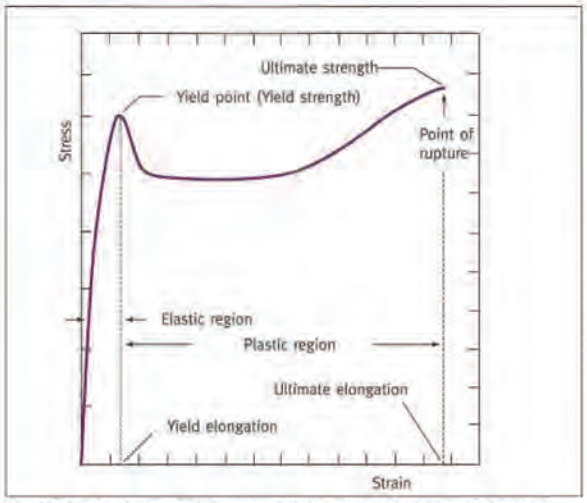


Fig 20-1 Typical tensile stress-strain curve for thermoplastic.

When generating a stress-strain curve, it is important to keep in mind the nature of the deformation. Three important modes of deformation for aligners are tension, bending, and torsion, and therefore these deformations should be evaluated when testing aligner materials. American Society for Testing Materials (ASTM) test D638-96, Standard Test Method for Tensile Properties of Plastics, is one of the most widely used and fundamental of all material tests and describes methodology for determining material properties while the material is subjected to tensile forces. A typical tensile stress-strain curve for a thermoplastic material under tension is shown in Fig 20-1. Data were generated using an Instron testing machine in which one end of the test specimen is clamped in a loading frame and the other subjected to a controlled load or force. From this simple curve we can learn much about the mechanical properties of this material.

Material modulus

The most important and fundamental characteristics of any material are the moduli. The modulus is defined as the ratio between the applied stress and the corresponding material deformation. For materials evaluated under tension, the constant of proportionality is the modulus of elasticity or Young's modulus, denoted E:

$$\sigma = E\pi$$

where σ is stress and π is strain. Young's modulus is a unique characteristic for a given material and is consid-

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ered by scientists and engineers as a measure of material "stiffness." For aligners, a material should possess sufficient stiffness to generate forces and moments on teeth; however, if the material modulus is too high (very high stiffness), then the patient will experience difficulty with the insertion and removal of the aligners. Similarly, a material with a very low modulus may not provide sufficient force to move teeth.

Elastic region

In the low strain portion of the curve (small deformations), many materials obey Hooke's law to a reasonable approximation, so that stress is proportional to strain. In this region, the curve exhibits linear elastic behavior. If stress is removed, the material returns to its original shape and length.

Yield point

The yield point is the first point at which an increase in strain occurs without an increase in stress. In general, thermoplastics with high yield points are desirable for fabricating aligners.

Plastic region

The area between points 5 and 6 is known as the *plastic region* because the material will not return to its original shape and length after the stress is removed.

Ultimate tensile strength

Ultimate tensile strength is the maximum stress a material can withstand before rupturing.

Material toughness

Toughness is a measure of the energy a sample can absorb before it ruptures. It is found by calculating the total area under the stress-strain curve.

Elongation

Elongation is the strain that the material undergoes while being stressed. Elongation is typically measured at the material yield point or at the material break point.

Data generated from stress-strain curves on standardized samples are valuable for understanding the mechanical properties by which alternative aligner materials may be evaluated. These curves may also aid in the prediction of aligner performance for short-term loads. As an example, consider the short-term forces applied to aligners as they are removed from a patient's dentition. The duration of these forces is short, often on the order of seconds. During this period, however, the aligner may undergo severe deformations. For short-term loads, it is critical that an aligner respond in an elastic manner if it is to return to its original shape. An understanding of elastic properties may be derived from a stress-strain curve for a particular material. In the above situation, we seek a thermoplastic material that exhibits substantial linear elastic behavior along with a high yield point.

Forces applied over a long duration

As mentioned above, for small strains or deformations, thermoplastics follow Hooke's law for elastic materials; $\sigma = E\pi$; stress σ is proportional to strain π. In reality, it is well-known that thermoplastic materials deviate from Hooke's law in various ways because they exhibit viscous (liquidlike), as well as elastic (solidlike), characteristics. Because of this behavior, scientists and engineers refer to thermoplastics as viscoelastic materials. Importantly, for these materials the relationship between stress and strain depends on time. Therefore, thermoplastic materials used in aligner fabrication exhibit viscoelastic behavior that can have a profound influence on the performance of aligners in vivo.

A fundamental time-dependent material property of thermoplastics is stress relaxation, which is defined as the gradual decrease in stress when a material is held at constant strain. Strain develops in aligners in regions with programmed tooth movement. The aligner's elastic nature allows it to deform and stretch to accommodate the programmed movement. Because of the viscoelastic nature of the aligner thermoplastic, the force generated by the programmed movement decreases as a function of time.

Stress relaxation processes are usually accelerated by the presence of moisture. The severity of this effect depends on the nature of the plastic, the amount of water absorbed, the temperature, and the severity of the loading to which the part is subjected.

Nonmechanical properties

While it is clear that material mechanical properties affect aligner performance, there are also many material nonmechanical properties that are of critical importance.

Thermal properties

Align Technology uses a thermoforming process that draws an extruded thermoplastic sheet over a stereolithographic mold to form an aligner. Since each aligner is unique, the thermoforming process is more suitable than

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an injection molding process where the same part is made in a large quantity. The thermoforming process, however, is highly dependent on processing temperatures, and consequently it is critical to understand the material's thermal properties. The most obvious thermal properties of a thermoplastic are its melting or softening temperatures, and temperature variations with regard to mechanical properties, such as tensile modulus, yield strength, and hardness. The glass transition temperature may be defined as the temperature below which the polymer is "glassy" and above which it is "rubbery." "Glassy" implies brittleness, and "rubbery" suggests flexibility. It was previously mentioned that semicrystalline polymers do exhibit a melt point, whereas amorphous polymers do not. Glass transition and melt temperatures may be determined using a differential scanning calorimeter (DSC). These tests indicate when softening occurs and whether it occurs gradually or suddenly. Understanding these two material properties allows for a better understanding of the thermoforming process with respect to the uniformity of heating, the effect of temperature on a material's drawing properties and thickness profile, and the window of temperature variability that can be tolerated.

Chemical resistance

When fitted on the dentition, aligners are constantly bathed in dental fluids such as saliva and crevicular fluid at a constant body temperature (37°C). Besides water, there are many constituents of saliva. Common inorganic constituents include bicarbonate, calcium, phosphorous, fluoride, magnesium, and trace metal ions. The major organic salivary components are proteins and small peptides. The presence of moisture, salivary components, increased temperature, and the constant mechanical stresses that are simultaneously acting on an aligner can adversely affect its performance. Water is especially notorious, as it may react chemically with the polymer backbone chain through a process termed *hydrolysis* and irreversibly degrade many polymers. Polymers particularly susceptible to water degradation are polyesters, polyamides, and polycarbonates.

Optical properties

One of the features that distinguishes aligners from traditional orthodontic appliances is that they are invisible when worn. This requires that aligner thermoplastic materials have suitable optical properties. The morphology of a thermoplastic polymer has a major effect on such optical properties as refraction, absorption, reflection, and scattering of light. Highly crystalline polymers are typically opaque because they tend to scatter visible light and decrease transmission. In general, amorphous polymers exhibit good light transmittance and are either transparent or translucent. Materials evaluated for use as aligners should transmit at least 80% visible light. Examples of amorphous polymers with good optical properties are polyurethane, polycarbonate, polysulfone, and polyester.

Biocompatibility

Aligners are medical devices and consequently require biocompatibility assessment to assure safety of the device. Safety data can be obtained by testing according to certain prescribed or recommended guidelines, including guidance documents developed by the International Organization for Standardization (ISO) and the US Food and Drug Administration (FDA). These guidelines include ISO 10993, "Biological Evaluation of Medical Devices," and the guidance document released by the FDA in 1995, "Use of International Standard ISO 109333, Biological Evaluation of Medical Devices." These guidelines provide a framework to aid manufacturers in the assessment of device biocompatibility. The number and type of specific safety tests required to assess product safety and compliance are dependent on the individual characteristics of the device, its component materials, and its intended clinical use. Ultimately, it is the responsibility of the manufacturer to select and justify the specific tests most appropriate for the establishment of product safety and compliance with regulatory requirements.

It may not be necessary to conduct biocompatibility tests on a device if it is made of materials that have been well characterized chemically and physically in the published literature and that have a long history of safe use. Typically, for new devices, biocompatibility testing and evaluation are performed to determine the potential toxicity from contact of the device with the body. The device materials should not, either directly or through the release of their material constituents, produce adverse local or systemic effects, be carcinogenic, or produce adverse reproductive and developmental effects.

Experimental Methods for Evaluating Aligner Materials

There are many possible approaches for systematically screening aligner materials. One approach is shown in Fig

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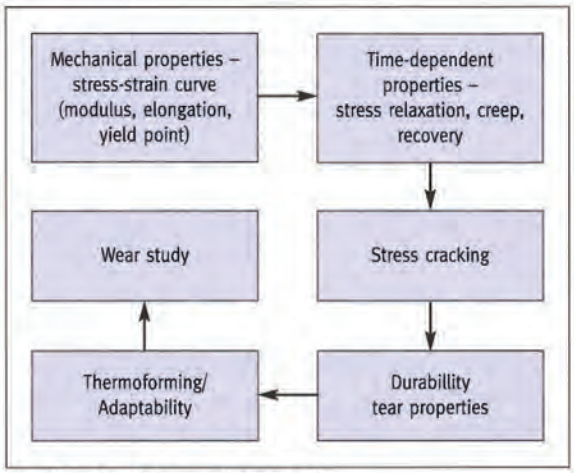


Fig 20-2 Material screening method.

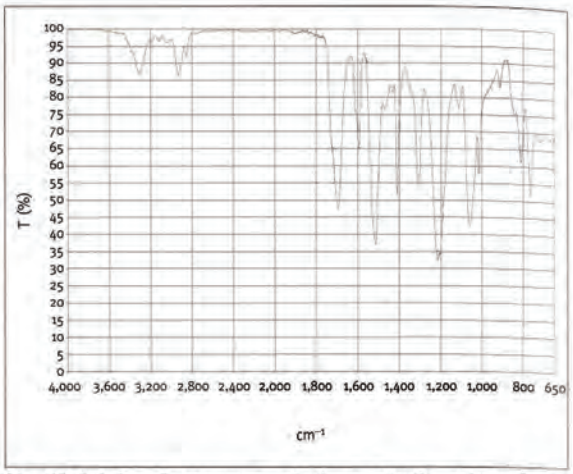


Fig 20-3 Infrared spectrum of thermoplastic polyurethane. T = Transform.

Table 20-1 Data provided on a typical specification sheet for polyurethane thermoplastic

Property	Test method (ASTM*)	Value
Specific gravity	D792	1.215
Mold shrinkage	D955	0.005 in/in
Tensile strength at yield	D638	9,140 psi
Tensile strength at break	D638	9,150 psi
Elongation at yield	D638	4%
Elongation at break	D638	170%
Tensile modulus	D638	309,000 psi
Flexural modulus	D790	286,000 psi
Rockwell hardness (R scale)	D785	118.2
Deflection temperature under load (66 psi, unannealed)	D648	167.9°F

**(ASTM) American Society for Testing Materials*

Table 20-2 Typical mechanical properties of amorphous polyamide and polyester

Property	Amorphous polyamide	Polyester
Stress at yield (psi)	9,400	7,800
Strain at yield (%)	5.5	4.6
Tensile strength (psi)	21,000	8,500
Elongation at break (%)	55	85
Tensile modulus (psi)	435,000	260,000

20-2. Whenever possible, efforts are undertaken to evaluate samples under conditions encountered in vivo. This is accomplished by making modifications to laboratory equipment that allow for the use of artificial saliva and temperature conditions approximating 37°C.

If one is to seek information on a particular material, a good place to start is with the supplier data sheet. These data sheets usually contain a wealth of technical information that has been generated using test procedures developed by reputable organizations such as the American Society for Testing and Materials (ASTM). An example of the information provided on a typical supplier data sheet for a thermoplastic polyurethane is shown in Table 20-1.

Polymer chemical structure

Polymer molecular structure may be investigated using spectroscopic techniques. Probably the most important spectroscopic technique used is infrared (IR) spectroscopy, which itself includes Fourier transform infrared (FTIR) detection. The principles behind IR spectroscopy are straightforward: IR radiation is used to excite the polymer molecules, typically between 600 and 4,000 cm. The amount of IR energy absorbed depends on the type of functional groups present as well as the quantity. Absorbed energy is reflected on an IR scan as a characteristic IR band. An infrared spectrum for a thermoplastic polyurethane is shown in Fig 20-3.

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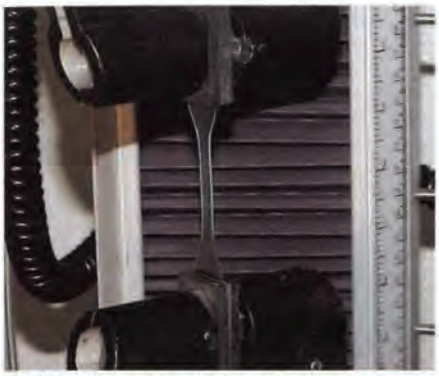


FIG 20-4 Instron tensile test setup.

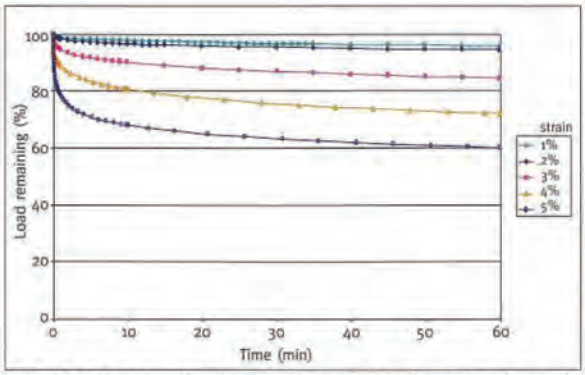


FIG 20-5 Stress relaxation properties of thermoplastic polyurethane (Ex30) at different strains (in ambient temperature and humidity).

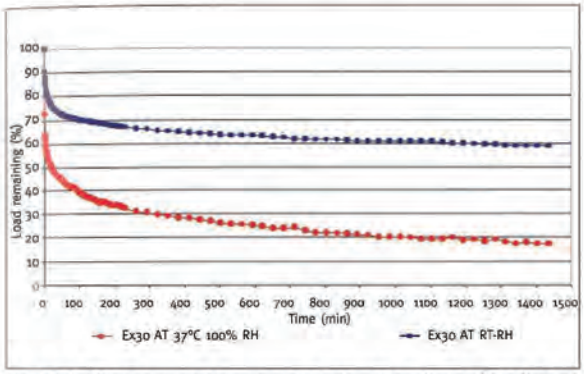


FIG 20-6 Stress relaxation properties of polyurethane (Ex30) in air and in 100% relative humidity (RH) following 5% strain. (RT) Relative temperature.

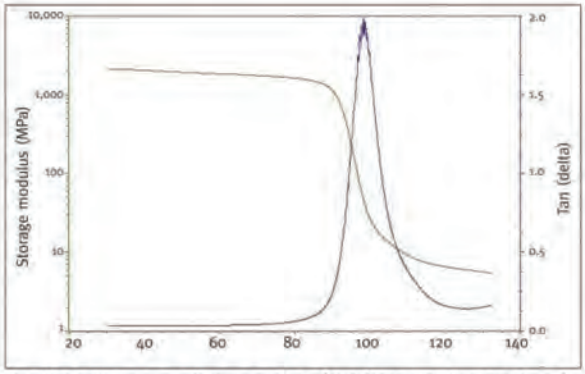


FIG 20-7 Storage modulus and tan (delta) versus temperature for thermoplastic polyurethane (Ex30).

Material mechanical properties

As discussed earlier, material short-term mechanical properties may be evaluated through the generation of stress-strain curves, which has been done for two thermoplastic materials: a polyamide and a polyester. Data were generated using an Instron testing machine in which one end of the test specimen is clamped in a loading frame and the other subjected to a controlled load or force (Fig 20-4). From this test, the various mechanical characteristics can be determined (Table 20-2).

Longer-term time-dependent material properties may be evaluated by stress relaxation and creep recovery. The stress relaxation properties for a polyurethane material are shown in Fig 20-5. The data in Fig 20-6 compare the stress relaxation properties for polyurethane in air and in 100% relative humidity. This example illustrates the adverse effect moisture can have on long-term thermoplastic properties.

Material thermal properties

Thermal analysis involves measuring a mechanical or physical property as a function of temperature or time. Common methods used in thermal analysis are differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), and dynamic mechanical analysis (DMA).

DMA allows an investigator to measure both the elastic (G') and viscous (G") components of a viscoelastic polymer while it is being subjected to a sinusoidal stress. It is a standard thermal analysis tool. The example below shows a DMA evaluation undertaken to characterize material morphology and thermal properties of a polyurethane. Figure 20-7 shows the storage modulus and tan (delta) at different temperatures for a polyurethane material. The storage modulus decreases slightly with increasing temperature from 30°C to 80°C and dramatically decreases from 80°C to 105°C. The temperature at the midpoint of the curve corresponds to the glass transition temperature.

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FIG 20-8 Adaptation block.



FIG 20-9 Stress cracking fixture.



FIG 20-10 Results of stress cracking test on Ex30.

Material adaptation

A thermoforming process is used for aligner fabrication. A thermoplastic sheet is first heated and then a vacuum/pressure thermoforming process is used to form the aligner. The hot sheet is drawn down over a stereolithographic (SLA) model of the patient's dental anatomy. Pressure and vacuum forces cause the material to adapt or conform to the SLA model. A special SLA was designed to evaluate how a material conforms to a particular geometry during the manufacturing thermoforming process. In this situation, heated sheets of material are drawn over SLA molds formed with V-grooves of varying depth (ie, 4 to 16 mm) (Fig 20-8). The depth to which the material penetrates is an indication of its ability to adapt during the thermoforming process. At a defined temperature, the level of adaptation for polyurethane is known to be superior to that of polycarbonate material.

Material stress cracking

Aligner surfaces are subjected to varying deformations (ie, strains) while worn in the oral cavity. Additionally, saliva and salivary components can affect aligner material performance. The ability of an aligner material to resist stress cracking while under strain is of paramount importance. In the environmental stress cracking test, material samples are subjected to strains (2%, 5%) on a metal fixture (Fig 20-9) immersed in artificial saliva at 37°C for up to 48 hours. At the end of this time, samples are removed and dried for visual inspection (Fig 20-10). The tensile properties for each sample are evaluated using an Instron machine. Results show that neither polycarbonate nor polyurethane exhibits stress cracking after immersion for 48 hours in artificial saliva. Although tensile properties (eg, yield at strain, tensile strength, modulus, etc) for these materials decreased, both materials exhibited similar changes after immersion in artificial saliva for 48 hours.

Aligner durability

This test was designed to simulate aligner wear in vivo. In this test, aligners are subjected to cycling (ie, repeated insertion and removal steps) on a typodont attached to a fatigue tester. Two types of typodonts are utilized for this study: a lower-stage typodont based on a moderate occlusion with few attachments and an upper-stage typodont based on severe occlusion and a significant number of attachments. Typodonts with aligners are soaked in artificial saliva at 37°C for up to 2 weeks. Aligners are removed on a daily basis and subjected to 12 cycles on the fatigue tester. Aligners are checked for defects (eg, cracks, tears) at the end of each cycle. Aligners fabricated from three lots of each material performed in a similar manner over a 2-week test period.

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In vivo aligner wear study

A clinical evaluation was conducted to evaluate and compare the materials while being worn in vivo. For this study, tooth movements were not programmed into aligners. A total of 14 volunteers were recruited from the company. Study participants received an oral examination and were asked to complete an informed consent form before being admitted into the study. Each participant was randomly assigned one Ex30 aligner and one Ex30-X4995 aligner (split-mouth design). They were also requested to maintain a daily diary form to keep track of the number of their aligner wear schedule. At the end of the 3-week study, participants were asked to turn in their aligners and to complete a material evaluation form covering the following categories: mouth dryness, aligner fit, aligner color, ease of aligner removal, and feeling in the mouth.

Results from this study showed no significant differences in material behavior for the following categories: mouth dryness, aligner fit, ease of aligner removal, and feeling in the mouth. For aligner color, however, maxillary aligners based on Ex30-X4995 exhibited less discoloration (yellowing) compared to aligners made from Ex30.

Conclusion

Data presented in this chapter should help the clinician to understand the performance range and characteristics of aligners. Moreover, it should lead the operator to be more conservative while working with the ClinCheck images. But most significantly, it should make clear that longer wear times might be necessary for certain types of tooth movements.

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chapter 21

Ex40 Material and Aligner Thickness

by
Trang Duong, DDS; Eric Kuo, DDS; and Mitra Derakhshan, DDS

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Finishing in orthodontics requires precisely controlled force application to achieve the final alignment. With conventional fixed appliances, stiff rectangular stainless steel or titanium molybdenum alloy (TMA) wires are used to achieve these precise movements. Detailing bends are placed in the wires to achieve the final movements required for finishing. The Invisalign System shares this goal of precise control of tooth movements with fixed appliance techniques. Theoretically, the use of a thicker material increases the control of tooth movement because of the increased stiffness. Based on data from a University of Washington study on material stiffness and the case refinement, the idea of using a thicker polyurethane material (Ex40) during Invisalign treatment to reduce the case-refinement rate was explored.

Currently, Invisalign appliances are fabricated from a polyurethane material of 0.030-mil thickness (Ex30). Although generally effective through early stages of tooth movement, Ex30 appliances have led to some difficulties in achieving the desired final detailing at the end of treatment. Currently, additional case-refinement aligners—or other auxiliaries such as detail pliers, buttons/elastics, or even sectional wires—are used to finish cases. Align Technology's retention material is the same polyurethane material used to fabricate the aligners; the difference is that it has a thickness of 0.040 mil (Ex40). This chapter explores the idea of using a thicker polyurethane material (Ex40) during Invisalign treatment to reduce the case-refinement rate.

Effects of Thickness on the Elastic Properties of Polyurethane Materials

Reports on the material properties of various archwires used in orthodontics are copiously available in the literature. Regardless of the material, the elastic properties—strength, stiffness, and range—are greatly affected by changes in the geometry of the wire. Both the cross section (whether the wire is round, rectangular, or square) and length of the wire determine its properties. Studies on the material properties of archwires are conventionally done using beams. The method of support for the beam determines how the elastic properties will change. For example, in a cantilever beam supported by one end, doubling the diameter of the wire increases its strength eight times. Regardless of how the beam is supported, however, changes in the diameter of a beam greatly affect its properties. Changes in the length of an archwire also affect its properties. For example, if the length of a cantilever beam is doubled, its strength is halved but its springiness increases eight times and its range four times. These properties usually cannot be changed with aligners because the shape and length of tooth-cupping polyurethane material are determined by arch and tooth anatomy. The thickness or diameter, however, can be changed with aligners. For example, increasing the thickness of aligners from 0.030 to 0.040 mil increases the stiffness by approximately one third.

A study was undertaken to determine if using a thicker polyurethane material (Ex40) at the end of Invisalign treatment reduced the need for additional case-refinement aligners. It was found that thicker materials worn at the end of treatment slightly improved the alignment but did not eliminate the need for additional aligners. Another study was launched to further evaluate the effectiveness of Ex40 in Invisalign treatment.

The primary objectives of this latter, randomized trial were to explore (1) the effectiveness of Ex40 aligners in the Invisalign treatment process and (2) the effect of Ex40 on the prevalence of case refinement/midcourse correction. A secondary goal of the study was to obtain descriptive data related to potential risk factors associated with wearing an Ex40 aligner. The parameters evaluated included amount of root resorption, oral hygiene, plaque, tooth sensitivity, and temporomandibular joint changes.

The patients were recruited from the Ferrara, Italy, area. There were no exclusions based on gender or race. All patients were in the adult dentition with growth completed. Any malocclusion was accepted in the study except cases requiring premolar extractions, major extrusions, rotations of round teeth, and molar uprighting. In addition, patients with periodontal disease or active caries who did not have a dentist or periodontist of record were excluded and referred for treatment. Patients with preexisting and active symptoms of temporomandibular disorders were also excluded from the study. The patients had to be willing to undergo at least one midcourse correction (but no more than two) throughout the treatment process.

Patients were randomly assigned to one of two groups on an alternating basis (ie, the first person enrolled was assigned to group 1, the second person enrolled was assigned to group 2, etc.) until 15 patients were in each group. Patients assigned to group 1 were treated with the

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following aligners: every fifth aligner was made out of Ex40, and the patient wore this aligner for 2 weeks and then progressed to the next aligner. The last aligner was made from Ex40. Patients assigned to group 2 were treated with the following aligners: the entire group used aligners made from Ex30 with the last five aligners in Ex40. The speed of tooth movement was the same for both groups with a maximum ranging from 0.15 to 0.20 mm of tooth movement per stage (current manufacturing guidelines). The ClinChecks for both groups were set to ideal alignment at the end of treatment with no programmed overcorrection.

For group 1, one patient dropped out, two finished treatment and did not have refinement, eight went into refinement, one is under review for refinement, and three are still in the initial treatment series of aligners. For group 2, one patient dropped out, one finished treatment and did not have refinement, six went into refinement, one patient had a midcourse correction, and six are still in the initial treatment series of aligners.

Preliminary conclusions of the study indicate that there is no difference in the case-refinement rate of the two groups. Neither the use of a thicker material (Ex40) for every fifth aligner nor for the last five aligners seems to reduce the case-refinement rate. Clearly, more data are needed if the use of a thicker material might reduce the case-refinement rate.

Finishing with Invisalign

When Andrews introduced the straight-wire appliance in the 1970s, he changed the way orthodontics was practiced. His ideas greatly increased the efficiency and efficacy of fixed appliances.[1] Instead of adding first-, second-, and third-order bends for each tooth, this information was programmed into the bracket. Interestingly, when the appliance was introduced, there was a misconception that wire bending would become obsolete because the bracket would do all the work. Although the prescription bracket greatly reduced the amount of archwire bending required to treat a case, it did not eliminate the need. The clinician still placed subtle bends along the archwire or used additional finishing techniques (eg, rubber bands and positioners). Finishing still required bracket repositioning and detailing bends to achieve the desired results. Factors responsible for this included inaccurate bracket placement, variations in tooth anatomy, tissue rebound,

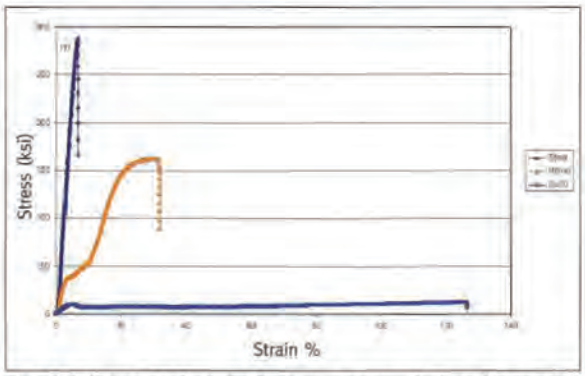


FIG 21-1 Stress-strain curve for 0.017 × 0.017–inch stainless steel and nitinol, and Ex30. Ex30 is more ductile than the metals.

and play between the bracket slot and archwire.[2,3] Rarely are cases finished with only brackets and a straight archwire.

As with fixed appliances, several factors play an important role in finishing with Invisalign and can affect the anticipated results. Because of the overlay design of the appliance, the anatomy of the tooth plays an important role and can cause minor alignment discrepancies. Variations in tooth shape (eg, irregular facial surfaces, unusual crown shapes, and unfavorable crown shapes) require additional aligners to achieve the desired alignment. Tooth movement is dependent on the response of the periodontal tissues to an applied force. Variation in the biologic response to tooth movement and the viscoelastic properties of the periodontal tissues affect the treatment outcome. This tissue behavior is similar to "slot play" in fixed appliances, in that there exists a lag period. Additionally, a secondary lag is introduced based on the material properties of the aligners.

In an effort to improve the finishing regimen and also increase the predictability of achieving the desired treatment result, a study was conducted to determine if using a thicker polyurethane material at the end of treatment reduced the need for additional case-refinement aligners. Figure 21-1 shows the stress-strain graph comparing 0.017 × 0.017–inch stainless steel versus 0.017 × 0.017–inch nitinol and 0.030-mil polyurethane material (Ex30). The graph illustrates the difference in stress-strain characteristics of orthodontic wires compared to aligners. It also indicates that aligners produce a lower level of stress for a specified strain compared to wires, and that the amount of stress delivered is fairly consistent relative to the strain in contrast to wires.

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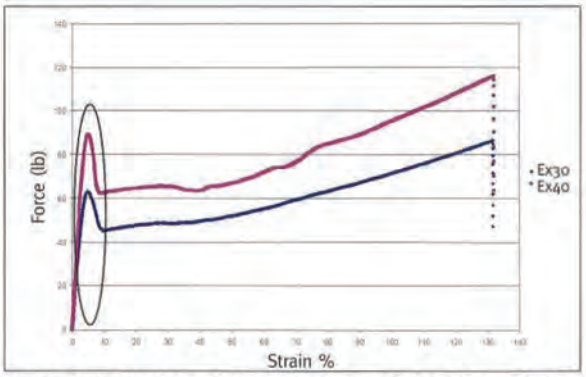


Fig 21-2 Comparison of stress-strain curves for Ex30 and Ex40 (maximum 5% yield strain). Area of stress-strain curve that pertains to aligners is circled.

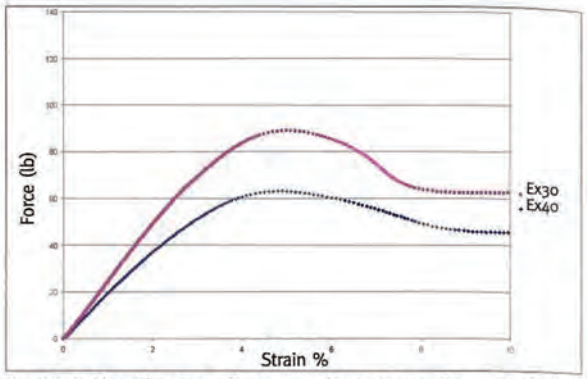


Fig 21-3 Magnification of area on the stress-strain curve that is used with aligners (circled in Fig 21-2). Increasing the thickness of the polyurethane material from 0.030 to 0.040 mil increases the stiffness by one third, which translates to a force increase of one third.



Fig 21-4 (a to e) Initial photographs.

In the study, patients wore their initial series of aligners and progressed to the next set every 2 weeks. After the initial set, the patients wore a duplicate last aligner in a thicker material (Ex40) for 2 weeks. Figures 21-2 and 21-3 show the stress-strain graphs comparing 0.030 mil (Ex30) and 0.040 mil (Ex40). By increasing the thickness from 0.030 mil to 0.040 mil, the stiffness increased by approximately one third. Following this aligner, the clinician evaluated the results and determined whether additional finishing aligners were required.

Alginate impressions were made at the end of the initial set of aligners (pre-Ex40) and then after the patient wore aligners made from the thicker polyurethane material (post-Ex40). If additional case-refinement aligners were required, alginate impressions were also made at this time (case-refinement aligners). The impressions were then poured and the models scanned. The individual time points were superimposed over the projected ClinCheck goal to determine the correlation between the goal and the actual achieved movements. Superimpositions were done using a best-fit algorithm. The maxillary and mandibular canines and incisors were evaluated via measurements of the in-and-out (labiolingual) and rotational movements.

The following case from this study did not require additional case-refinement aligners. The initial photos of this case show Class I maxillary spacing and mandibular crowding (Figs 21-4a to 21-4e). Figures 21-5a and 21-5b show the ClinCheck final position goal for the case. The treatment involved closing the maxillary spaces and alleviating the mandibular crowding through anterior interproximal reduc-

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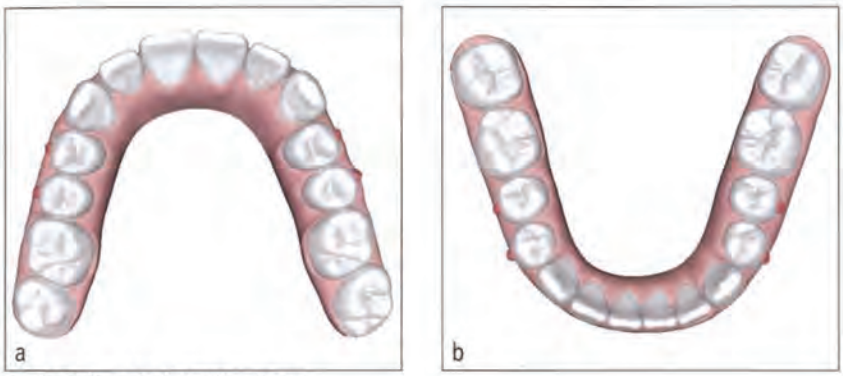


FIG 21-5 (a and b) ClinCheck goal.

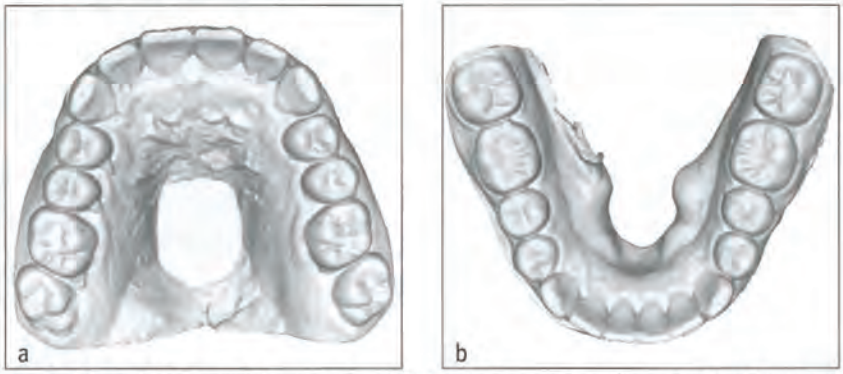


FIG 21-6 (a and b) Scanned images of models taken after the last aligner (pre-Ex40) was worn.

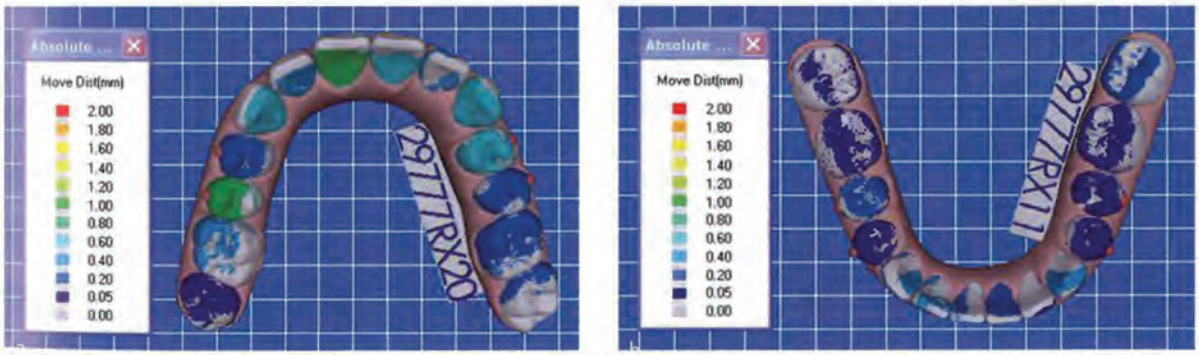


FIG 21-7 (a and b) Superimposition of pre-Ex40 models and ClinCheck goals. The legend on the left represents a color schematic of the difference (in millimeters) of the position of the teeth.

tion during treatment. The total number of aligners was 20 for the maxillary arch and 11 for the mandibular arch. After the last set of aligners (pre-Ex40) were used, alginate impressions were made and poured, then scanned into the computer (Figs 21-6a and 21-6b). The pre-Ex40 models were superimposed over the projected ClinCheck goal (Figs 21-7a and 21-7b), These figures show that, compared to the projected goal, a patient who wears only the initial series of aligners achieves a fairly good match with the actual treatment result. However, some teeth were slightly short of the projected goal. Specifically, the position of the maxillary incisors was short approximately 1 mm with the projected goal. Comparison of the pre-Ex40 and the projected ClinCheck goal superimposition of the combined maxillary and mandibular anterior teeth reveals that the in-and-out movements showed a strong correlation of .94 (Fig 21-8a), while the rotation movements showed a fairly good correlation of .85 (Fig 21-8b).

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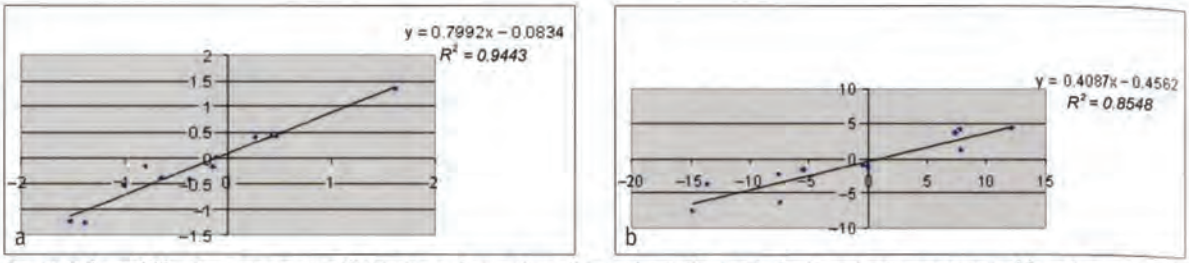


Fig 21-8 (a and b) Pre-Ex40 versus ClinCheck goal superimposition of anterior teeth for in-and-out movements (*a*) and rotation (*b*) (n = 1).

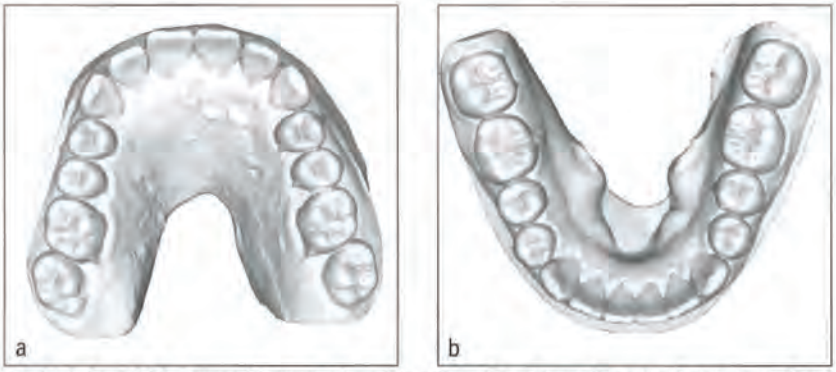


Fig 21-9 (a and b) Scanned images of models taken after aligner (post-Ex40) was worn for 2 weeks.

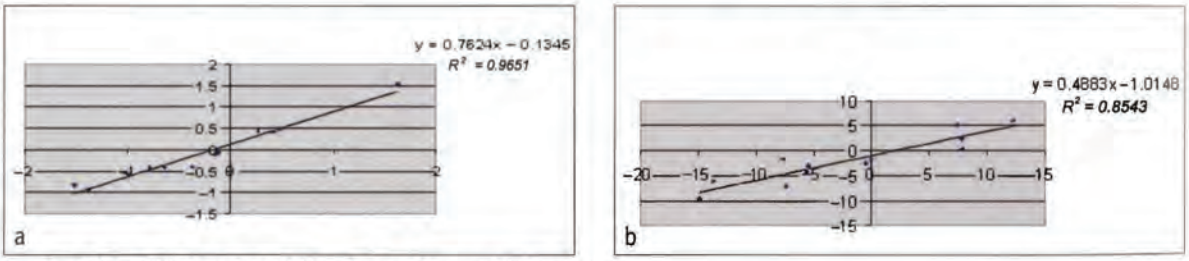


Fig 21-10 (a and b) Superimposition of post-Ex40 and ClinCheck goals.

Figures 21-9a and 21-9b show the scanned models after the patient wore Ex40 aligners for 2 weeks. When these models were superimposed over the ClinCheck goal, improved alignment compared to the pre-Ex40 models was evident (Figs 21-10a and 21-10b). The plot graph shows that the correlation improved slightly from .94 to .97 for the in-and-out movements and did not change in the rotational movements (Fig 21-11). This case shows that wearing Ex40 aligners at the end of treatment slightly improves the anterior alignment. This particular case did not require additional case-refinement aligners after wearing the Ex40 aligners, but some cases did.

Data for a pool of 14 patients were combined, and the resulting plot graphs showed a similar trend of improvement in alignment for in-and-out movements and rotation after wearing Ex40 aligners (Figs 21-12 to 21-14). However, even after wearing the Ex40 aligners, 5 of the 14 patients required additional case-refinement aligners. This data suggest that wearing Ex40 aligners at the end of treatment can slightly improve the anterior alignment. This also suggests that patients who use Ex40 aligners as retainers at the end of treatment can expect to achieve slight improvement in their alignment during the retention phase. Overall, the study showed that using a thicker aligner material at the end of treatment slightly improved alignment but did not completely eliminate the need for additional aligners.

The results from this study showed that, similar to fixed appliances, finishing with Invisalign sometimes requires

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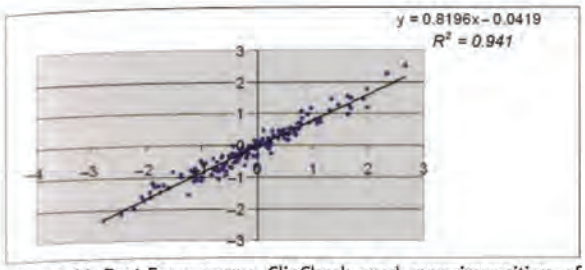


FIG 21-11 Post-Ex40 versus ClinCheck goal superimposition of anterior teeth for in-and-out movements (n = 1).

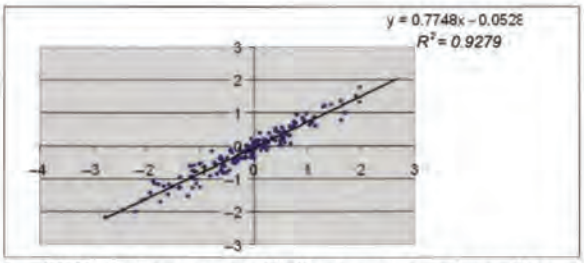


FIG 21-12 Pre-Ex40 versus ClinCheck goal superimposition of anterior teeth for in-and-out movements of patients (n = 14).

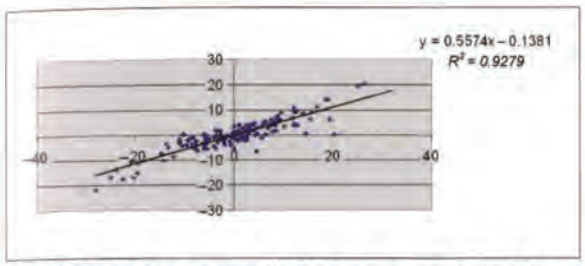


FIG 21-13 Pre-Ex40 versus ClinCheck goal superimposition of anterior teeth for rotational movements of patients (n = 14).

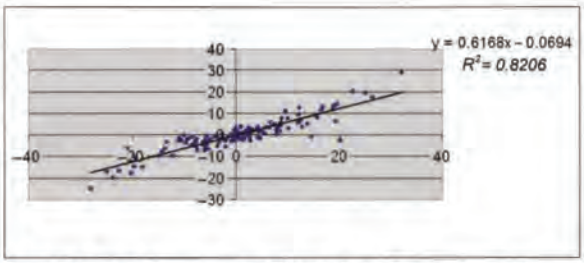


FIG 21-14 Post-Ex40 versus ClinCheck goal superimposition of anterior teeth for rotational movements of patients (n = 14).

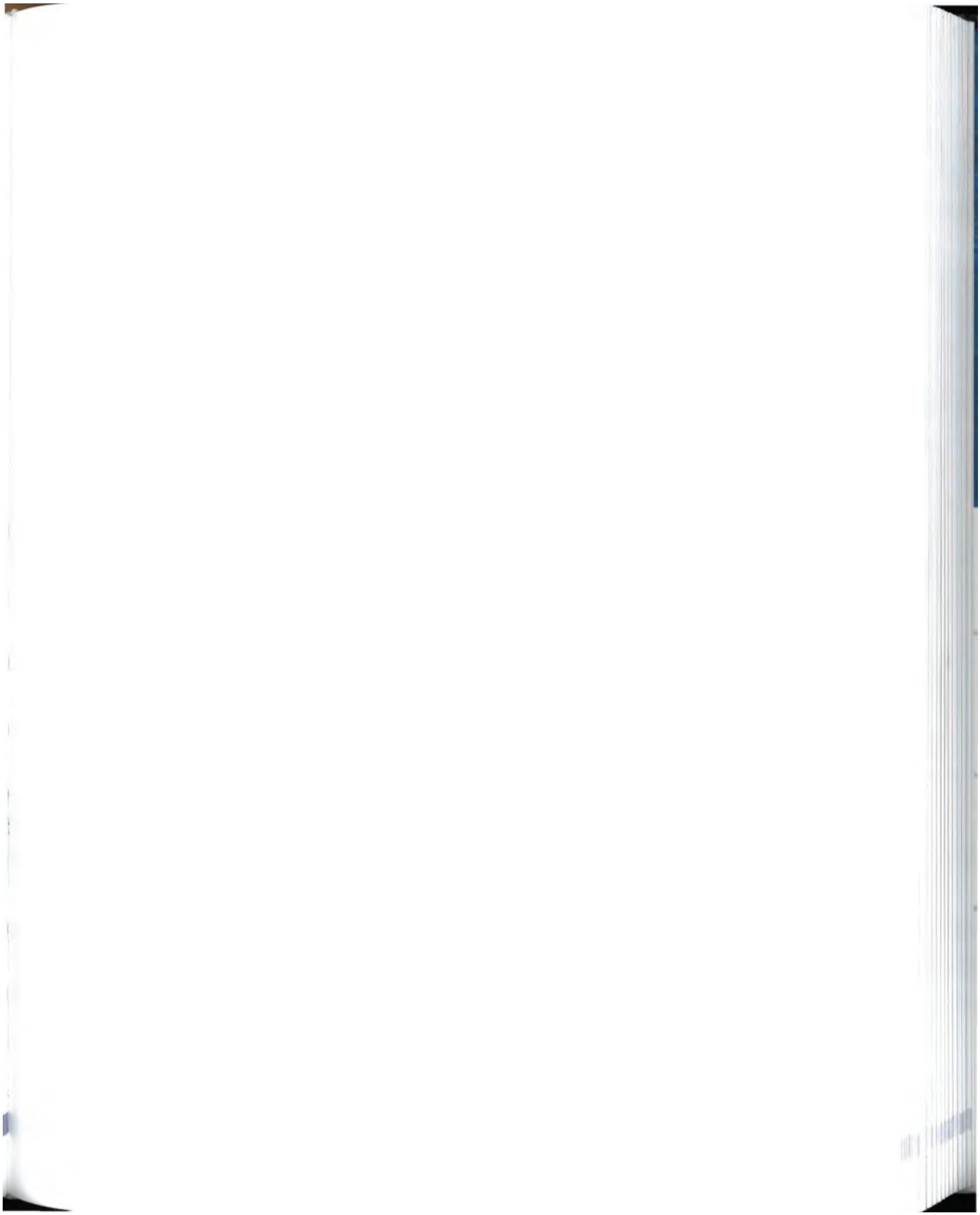
additional aligners and use of auxiliaries, such as detailing pliers, to achieve the desired treatment results. The best way to determine the need for additional movements is to wait until the last aligner is delivered and then clinically examine the teeth. This is the time when the precise amount and direction of additional movement can be requested on the specified teeth. This process is more effective and efficient than trying to guess at the beginning which tooth will require additional movement—and how much—to achieve full alignment. If the last aligner fits well and the movements do not exceed three aligners, additional aligners can be ordered to achieve the last additional movements. However, if the last aligner does not fit well and the case requires movements with more than three aligners, a new impression should be made.

Detailing pliers have proved successful at achieving movements at the end of treatments that require in-and-out movements and minor incisor rotations. There is a misconception with Invisalign treatment that the appliance performs all of the work and therefore that treatment requires simply dispensing the appliances. As with the prescription bracket, there is also a misconception that successful outcomes are based on a proper diagnosis and treatment plan and careful monitoring during treatment. Finishing a case with Invisalign may require additional aligners and other armamentaria to produce the desired treatment goals. Invisalign as a treatment modality can provide the clinician with the tools to offer patients an excellent esthetic treatment option. However, good clinical results are based on good case selection and careful monitoring during treatment.

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chapter 22

EXTRACTION TREATMENT WITH INVISALIGN

by
David E. Paquette, DDS

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TABLE 22-1 Optimal forces for orthodontic movement*

Type of movement	Force (g)
Tipping	50–75
Bodily movement (translation)	100–150
Root uprighting	75–125
Rotation	50–100
Extrusion	50–100
Intrusion	15–25

*Data from Proffit and Fields.[1]

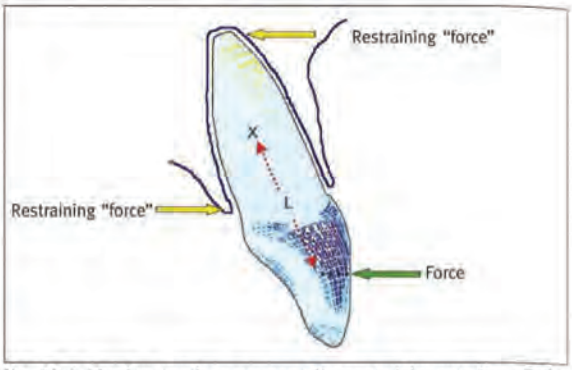


FIG 22-1 Tipping tooth movement is created by rotation of the tooth around the center of resistance. (X) Center of resistance; (L) moment arm.

Whether one is an advocate of extractions to facilitate orthodontic correction of a malocclusion or not, the fact is that even the most adamant extraction-averse orthodontist faces the occasion where extraction of one or more teeth is the only option. That said, proper control of root position and anchorage during closure of extraction spaces is the greatest challenge faced by any orthodontist. The question then becomes: Is extraction treatment with Invisalign a practical alternative to fixed appliances?

In 2000, Sims predicted that the future of orthodontics would include the abolition of bracket systems.[2] In his textbook *Contemporary Orthodontics*, Proffit stated that adult patients are often opposed to wearing conspicuous fixed appliances and would rather use a removable appliance.[1] He also described the characteristics required of an orthodontic appliance system:

> "No matter what the type of orthodontic appliance, it must meet certain basic design criteria: it (*1*) should not interfere with function; (*2*) should cause no harm to the oral tissues or interfere with the maintenance of good oral hygiene; (*3*) should be as light and inconspicuous as possible, yet sufficiently strong to withstand masticatory forces and a reasonable amount of abuse; (*4*) must be firmly retained in position; (*5*) must be capable of exerting an appropriately controlled force in the correct direction and delivering this force for as long as possible between adjustment visits; and (*6*) should allow control of anchorage, so that tooth movements other than those intended are minimized.[1 p475]"

On the surface it would appear that Invisalign satisfies all these criteria.

According to Proffit,[1] removable appliances are only capable of simple tipping movements and are easily displaced by the forces required to produce controlled root movement. He concluded that the usual solution to this problem was to use fixed appliances.

When the orthodontic department at the University of the Pacific began using aligners to treat more complex cases—such as those involving the extraction of a mandibular incisor—to determine if the space could be closed in a manner parallel to that of fixed appliances, they discovered that both the technique and the material had to be altered to move the teeth bodily. They are now experimenting with premolar extraction cases. Based on those experiences, it was concluded that "the use of the Aligners is far more complicated than most people believe. It takes a knowledgeable clinician with considerable experience to use the appliance to its maximum."[3]

To determine just what that maximum might be with Invisalign in its current rendition of aligner materials, we must examine the biomechanics of tooth movement with Invisalign.

Biomechanics

For all practical purposes, the problems involved with extraction treatment can be broken down to controlling torque and root parallelism. To properly discuss these issues, a review of several definitions of biomechanical terms is in order.

The first of these is force. *Force* is a load applied to an object that tends to move the object to a different posi-

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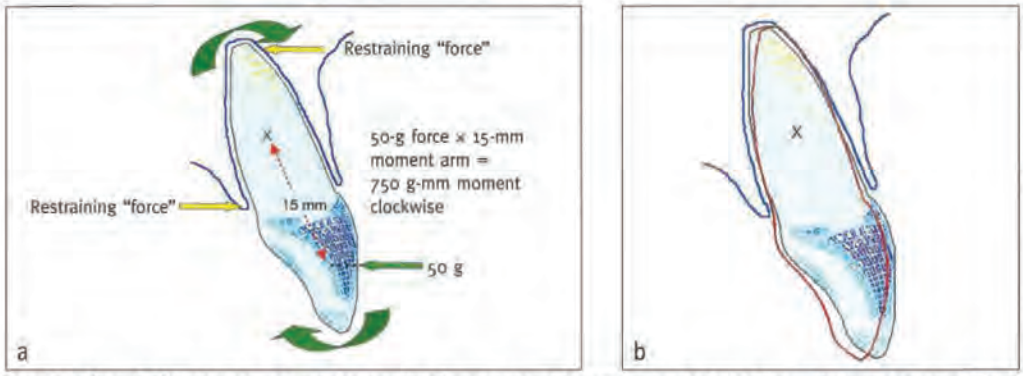


Fig 22-2 (a and b) Rotation around the center of resistance. The crown is displaced lingually and the apex facially. (X) Center of resistance and center of rotation are in the same location.

tion. Force, though defined in Newtons (mass times the acceleration of gravity), is usually measured in mass units of grams or ounces. Historically, the optimal amount of force required for most tooth movements has been considered to be 50 to 150 g (Table 22-1). Recent studies have suggested that given time, forces as low as 18 g are sufficient to produce bodily movement.[4] Because the force delivered with an aligner made from Align Technology's Ex30 polyurethane material is 200 g initially and decays to essentially a constant level of 40 g within hours, there should be no problem delivering adequate forces to the teeth to create desired movements. Controlling those forces then becomes the issue.

How the force is delivered and the reaction of the tooth to that force is a function of multiple factors. One of these factors is center of resistance. In engineering terms, *center of resistance* is a point at which resistance to movement can be concentrated for mathematical analysis. For an object in free space, the center of resistance is the same as the center of mass. If the object is partially restrained—as is the case for a pole or post embedded in the earth or a tooth root embedded in bone—the center of resistance is determined by the type of external constraints. The center of resistance for a tooth is roughly midway between the root apex and the crest of the alveolar bone.

If the point at which a force is applied to an object is not directly opposite the center of resistance, a moment is created. A *moment* is a force that acts at a distance and is defined as the product of the force times the distance to the center of resistance. It is measured in units of gram-millimeters or equivalent. If a force is applied at some distance to the center of rotation, not only will the force tend to translate the object in space, it will also tend to rotate the object around the center of resistance. This effect, of course, is precisely the situation when a force is applied to the crown of a tooth. The tooth is not only displaced in the direction of the force, but it is also rotated around the center of resistance—thus, there is a tipping tooth movement (Fig 22-1).

When there are two forces acting on an object that are equal in magnitude and opposite in direction, the combination of the two forces is referred to as a *couple*. The result of applying two forces in this way is a pure moment, since the translatory effect of the forces cancels out. A couple produces pure rotation, spinning the object around its center of resistance. The combination of a force and a couple can change the way an object rotates while it is being moved.

The point around which rotation actually occurs when an object is being moved is referred to as the *center of rotation*. When a force is applied directly to the middle of the facial surface of the crown, the tooth rotates about the center of resistance. This results in a tipping movement with the crown being displaced lingually and the apex of the root displaced slightly in a facial direction (Figs 22-2a and 22-2b).

If a force and a couple are applied to an object, the center of rotation can be controlled and made to have any desired location. The application of a force and a couple to the crown of a tooth, in fact, is the mechanism by which bodily movement of a tooth, or even greater movement of root than the crown, can be produced.

By applying a secondary force on the lingual at the incisal edge, a couple is formed that moves the center of rotation apically. The net lingual force combined with a couple

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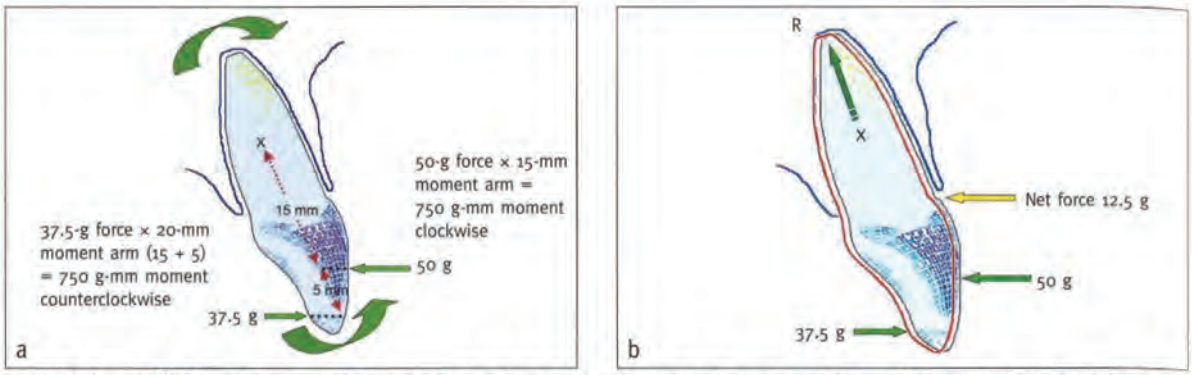


Fig 22-3 (a and b) Opposing moments form a couple that moves the center of rotation apically with a net force to the lingual that moves the tooth bodily. (X) Center of resistance; (R) center of rotation.

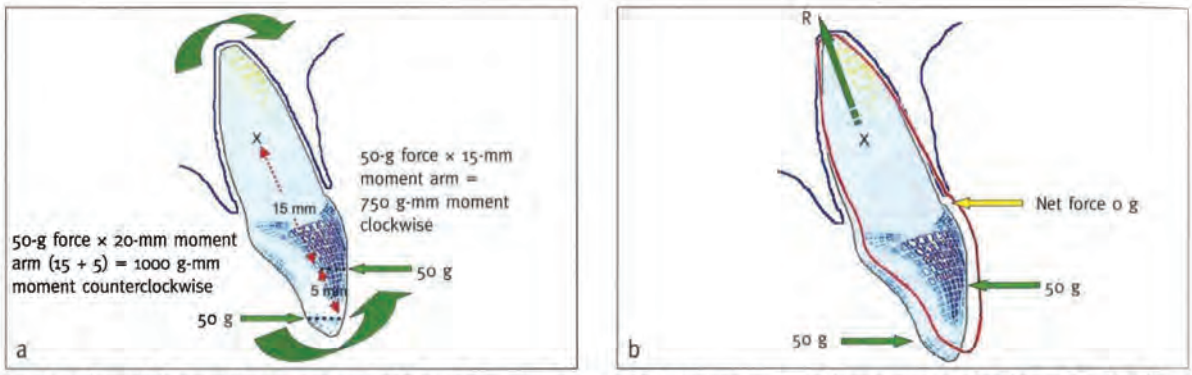


Fig 22-4 (a and b) Equal forces applied facially and lingually. Net counterclockwise moment of 250 g-mm results in rotation. The facial and lingual forces offset each other so there is no bodily movement. (X) Center of resistance; (R) center of rotation.

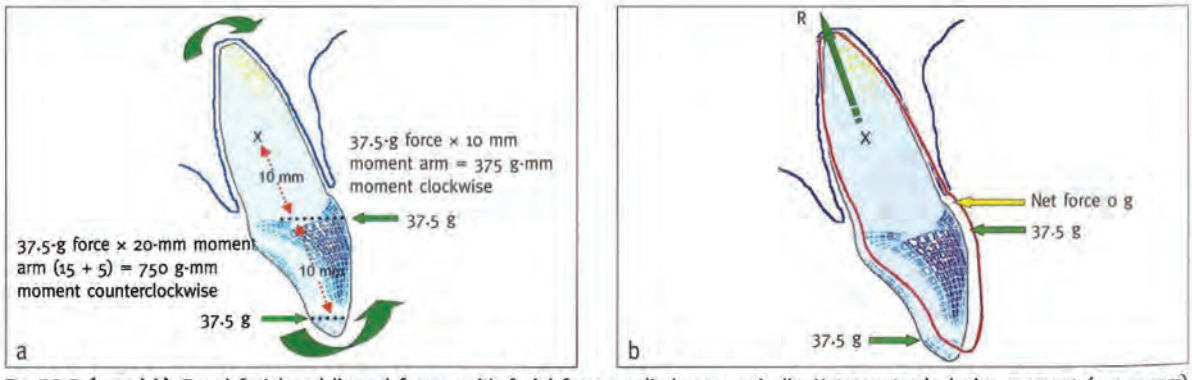


Fig 22-5 (a and b) Equal facial and lingual forces, with facial force applied more apically. Net counterclockwise moment (375 g-mm) results in rotation with no bodily movement. (X) Center of resistance; (R) center of rotation.

results in bodily movement of the tooth to the lingual. In this instance, forces applied to both facial and lingual surfaces produce the couple (Figs 22-3a and 22-3b).

By applying a secondary force on the lingual at the incisal edge equal to the force on the facial, a couple is formed that moves the center of rotation farther apically. The net lingual force in this case is zero. The net counterclockwise moment results in a rotational movement of the tooth with the apex moving slightly lingually and the crown moving facially (Figs 22-4a and 22-4b).

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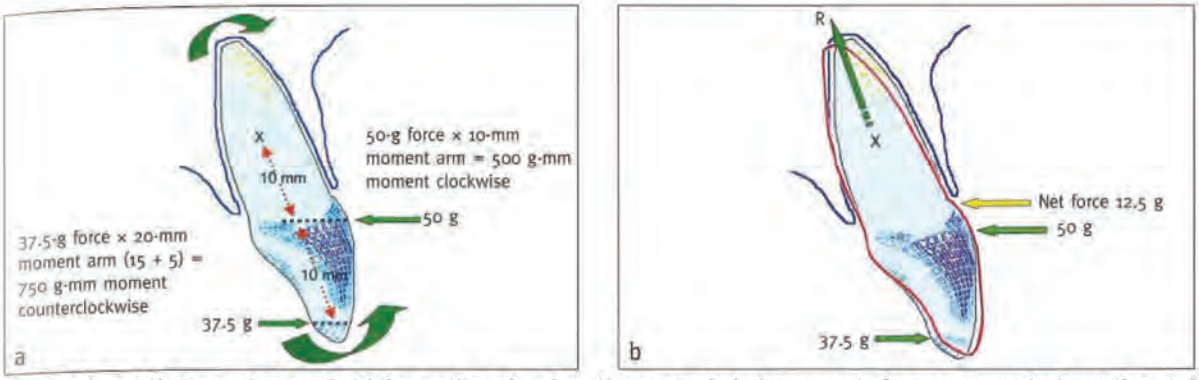


Fig 22-6 (a and b) Greater force on facial than on lingual surface. Net counterclockwise moment of 250 g-mm results in rotation, and net force produces lingual movement (lingual crown torque). (X) Center of resistance; (R) center of rotation.

By applying a smaller force to the facial closer to the apex and an equal secondary force on the lingual at the incisal edge, a similar couple is formed that also moves the center of rotation apically. The net lingual force in this case is also zero. The net counterclockwise moment results in a rotational movement of the tooth with the apex moving slightly lingually and the crown moving facially (Figs 22-5a and 22-5b).

Applying a slightly greater force to the facial and maintaining the secondary force on the lingual at the incisal edge forms a similar couple that also moves the center of rotation apically. In this case, however, the net lingual force is greater than zero. The net counterclockwise moment results in a rotational movement of the tooth with the apex moving lingually and the crown moving slightly facially (ie, lingual crown torque) (Figs 22-6a and 22-6b).

The goal is to control root position during movement to achieve the desired results with the least possible complexity. This can be achieved through control of the moment-to-force ratio. The ratio between the force applied to move a tooth and the counterbalancing moment used to control root position determines the type of tooth movement. If the ratio between the counterbalancing moment and the retraction force is less than 1, the tooth will tip just apically to its center of resistance. As the moment-to-force ratio increases, the center of rotation is displaced farther away from the center of resistance, producing controlled tipping. With a moment-to-force ratio of 8 to 10, bodily movement occurs. If the moment-to-force ratio is greater than 10, the root apex will be retracted more than the crown, producing lingual root torque (Fig 22-7).

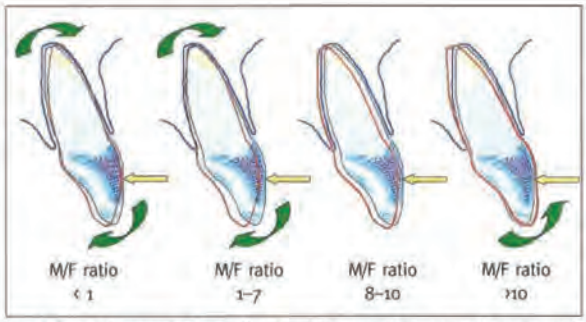


Fig 22-7 Moment-to-force (M/F) ratios used to control root position during movement.

Tooth-Aligner Biomechanics

Proffit stated in his textbook that removable appliances are

> "rarely satisfactory for adjunctive (or comprehensive) treatment. Removable appliances by their very nature produce simple tipping movements of teeth, making control of tooth position extremely difficult. In addition, removable appliances are by definition removable, and the adult patient's concept of continuous appliance wear does not always coincide with that of the dentist. Intermittent forces, though capable of producing tooth movement, are not as efficient as continuous forces, particularly in the presence of occlusal interferences."[1 p236]

He went on to say, "As a practical matter, it can be difficult to maintain removable appliances in place against the displacing effects of a pair of springs with heavy activation. The usual orthodontic solution is a fixed attachment on the tooth, constructed so that forces can be applied at two points".[1 p236]

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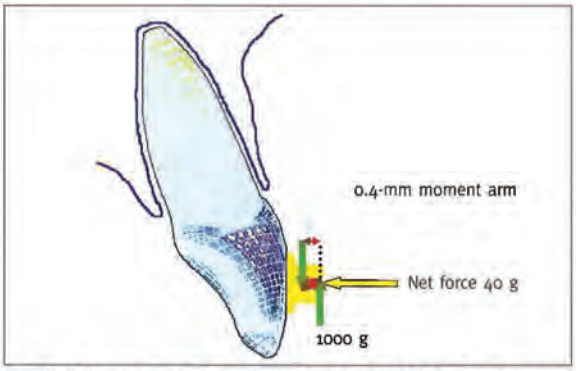


Fig 22-8 A moment-to-force ratio of 10 is needed for bodily movement. With a retraction force of 40 g and a moment arm of only 0.4 mm on a typical bracket, to avoid tipping the required moment is 400 g-mm, meaning a 1,000-g force at each corner of the archwire.

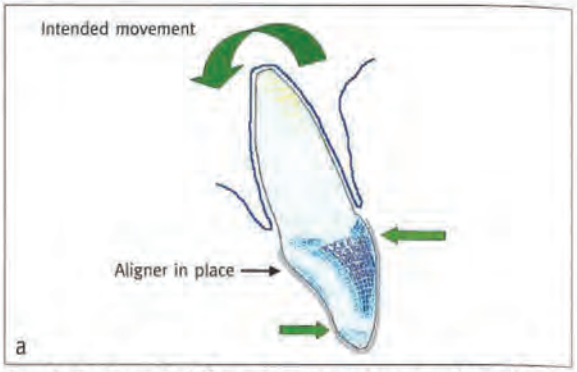


Fig 22-9a Theoretical force-moment system to achieve lingual root movement with an aligner.

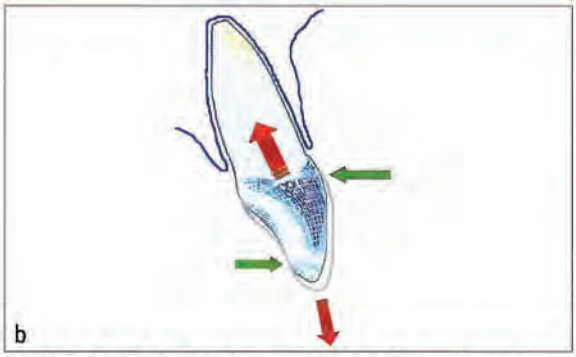




Fig 22-9 (b and c) Clinical expression of this force-moment system to achieve lingual root movement or bodily movement: The tooth is intruded or the aligner displaced as a result of lack of retention.

Torque control

To better understand the dynamics of root control with aligners, we will now examine the biomechanics of tooth movement with aligners and compare that with our understanding of movement with fixed appliances. Specifically, the design and placement of attachments and auxiliaries to accomplish controlled two-point force application will be examined.

One of the problems we see in attempts to move incisor roots with aligners is that the intended movement and the actual movement are often different. The reason for this is exactly what Proffit described for removable appliances in general: there is not enough retention to offset the force needed to generate the movement (Figs 22-8 and 22-9a to 22-9c).

The solution to aligner displacement is the proper design and placement of attachments. Figure 22-10 illustrates the evolution of attachments used to help eliminate this problem. The key is to provide a ledge for the aligner to grip that is perpendicular to the direction of displacement and of sufficient size to provide enough surface area to offset the force delivered. Another simple rule of thumb is to place the attachment far enough away from the gingival margin that the aligner will not spread or stretch and slip off the attachment.

Proper attachment design allows clinical expression of this force-moment system to achieve lingual root movement or bodily movement—that is, torque control. The moment arm is measured from the most incisal aspect of the attachment that extends to the effective gingival point of contact of the aligner. The effective point of contact near the gingival margin is approximately 1 to 2 mm from the gingival edge of the aligner as a result of stretch of the aligner in this area. Figures 22-11 to 22-14 illustrate the effect of attachment design and placement on torque control.

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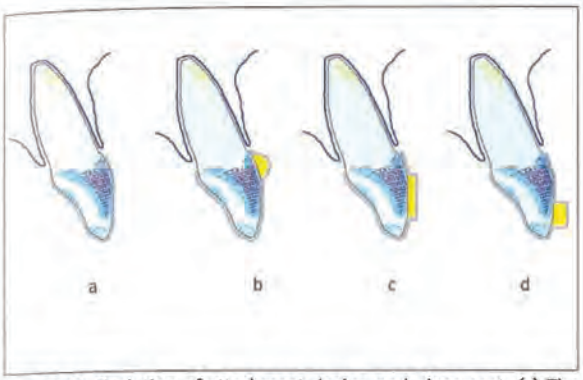


FIG 22-10 Evolution of attachment design and placement. (*a*) The aligner is easily displaced because there is no attachment or ledge to provide retention. (*b*) A ledge is created with an attachment, but it is placed too far gingivally and is inadequate for retention. (*c*) A ledge is created with an attachment, but it is placed too far gingivally and is too narrow for retention in this direction. (*d*) An attachment of proper design and placement, closer to the incisal edge and perpendicular to the direction of displacement, will provide sufficient retention.

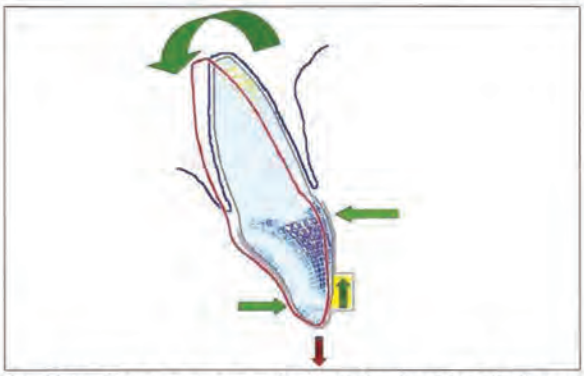


FIG 22-11 A 1 × 2 × 4–mm horizontal rectangular attachment placed near the incisal edge. The intrinsic, extrusive forces exerted on the aligner are now offset by the forces the attachment places on the "bubble" in the aligner. By providing a horizontal ledge 90 degrees to the force applied, retention of the aligner in its desired location is achieved, unwanted movements are reduced, and intended movements are enhanced.





FIG 22-12 **(a and b)** Rectangular attachments as viewed in ClinCheck and clinically (*arrows*).

Figure 22-12a illustrates a typical set of attachments as viewed on ClinCheck. The clinical appearance of these attachments is seen in Fig 22-12b. The trapezoid appearance seen on the virtual image is an artifact of the manufacturing process.

Figures 22-13a and 22-13b illustrate a recent modification to the horizontal rectangular attachment that produces a beveled appearance. The beveled attachment accomplishes two things: it allows easier aligner insertion and is esthetically superior in that it is less noticeable because of the lack of shadow along the incisal aspect of the attachment.

A net force of 40 g intended to move the tooth lingually would require a moment of 320 to 400 g-mm (F/M ratio, 8 to 10) for bodily movement or greater than 400 g-mm (F/M ratio, < 10) for lingual root movement (Figs 22-14a and 22-14b). Improper attachment design or placement allows the delivery of only 280 g-mm moment in conjunction with 40 g force, which results in controlled lingual crown tipping (Fig 22-14c).

Root parallelism

The other biomechanical consideration pertinent to extraction treatment is the controlled tipping to achieve root parallelism in the extraction sites. When a force is applied in an attempt to move a canine distally, the tooth will rotate around the center of resistance. It requires a sufficient moment to oppose the tipping movement. This is a more problematic area because in a typical extraction scenario, the aligner contacts the tooth in the buccal segments on a surface that is parallel to the direction of force. The result, of course, is that there is little, if any, moment arm created without the use of substantial attachments, auxiliaries, or both (Figs 22-15 to 22-17).

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FIG 22-13 (a and b) Beveled attachments accomplish the goals of retention and resistance to unwanted movement, are discreet, and facilitate insertion and removal of aligners.

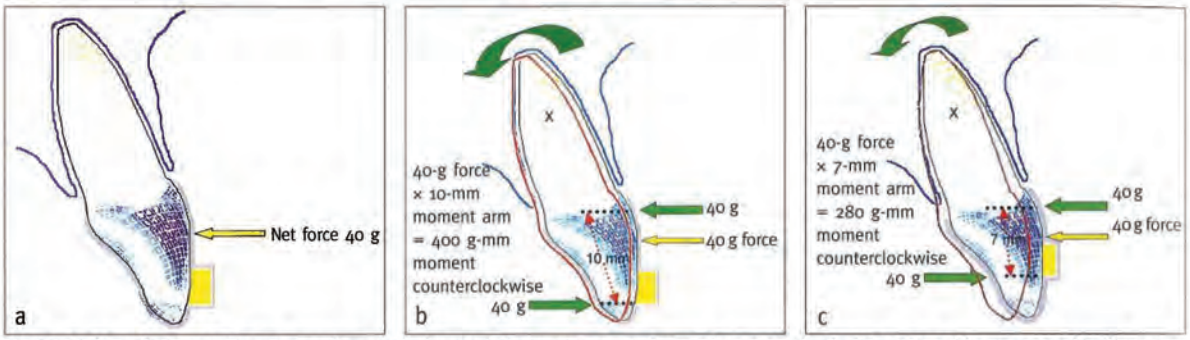


FIG 22-14 (a to c) Depending on attachment design and placement, a net force of 40 g on the facial surface (*a*) can create bodily movement (*b*) or lingual crown tipping (*c*). (X) Center of resistance.

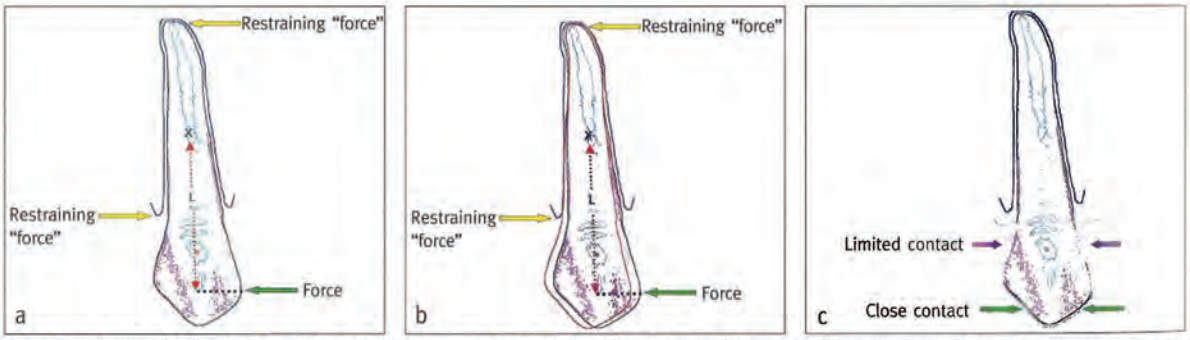


FIG 22-15 (*a and b*) The tooth rotates clockwise around the center of resistance. (*c*) Controlling movement of buccal segments can be difficult because of limited aligner contact in the direction of force application. To enhance force application requires placement of attachments and/or auxiliaries. (X) Center of resistance; (L) moment arm.

An idea dating back to the 1920s was to place an attachment on the gingival aspect of a bracket extending toward the center of resistance in an attempt to decrease the amount of tipping that occurs when teeth are moved mesiodistally. These gingival extensions are often described as *power arms*. A power arm can be added to the force system with Invisalign. The addition of a power arm auxiliary accomplishes two things. First, it moves the application of force closer to the center of resistance. Second, it creates a secondary moment as a result of pressure against the distal of the aligner. With the combined power arm and "T" attachment, it should be possible to control the distal root tip during retraction. This attachment design has been successful with some patients (Figs 22-18 to 22-23).

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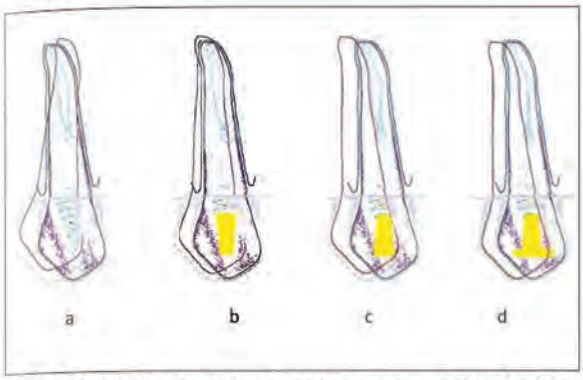


FIG 22-16 Attachment design and placement are critical to delivery of adequate couple to control root position but may still not be enough. Auxiliaries must be considered. (*a*) No attachment; tooth does not track with aligner. (*b*) Long vertical attachment helps provide couple but has intrusive vector and minimal retention. (*c*) Inverted long vertical attachment to provide couple has extrusive vector but still minimal retention. (*d*) "T" attachment design provides couple and added retention.

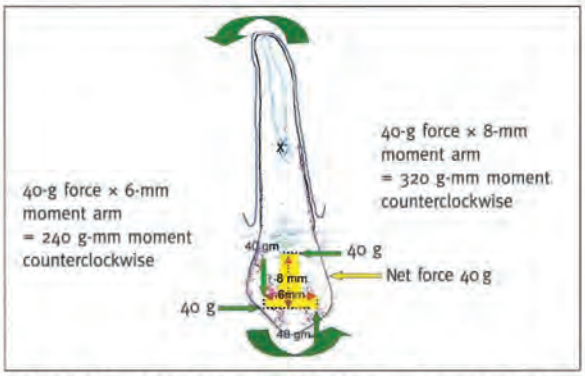


FIG 22-17 Combined 240-g-mm and 320-g-mm moments produce a 560-g-mm moment, assuming a full 40-g force at each corner.

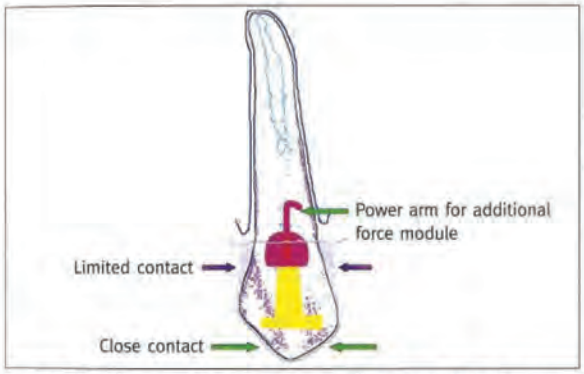


FIG 22-18 Addition of a power arm auxiliary and "T" attachment increases the likelihood of a proper force-moment system to control root movement during retraction.

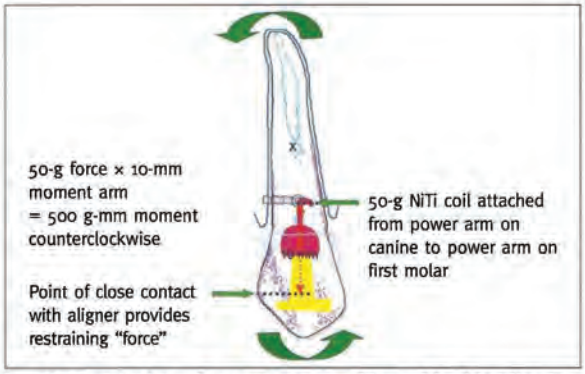


FIG 22-19 Addition of a power arm auxiliary with nickel-titanium coil adds additional retraction force.

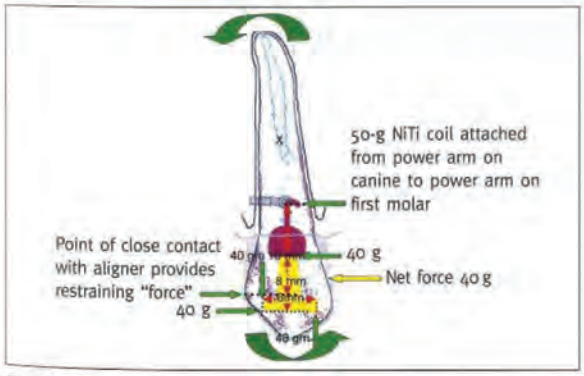


FIG 22-20 Force-moment system when attachments and auxiliaries are used. Combined 240-g-mm, 320-g-mm, and 500-g-mm moments produce a 1,060-g-mm moment with a 90-g distalizing force. (X) Center of resistance.

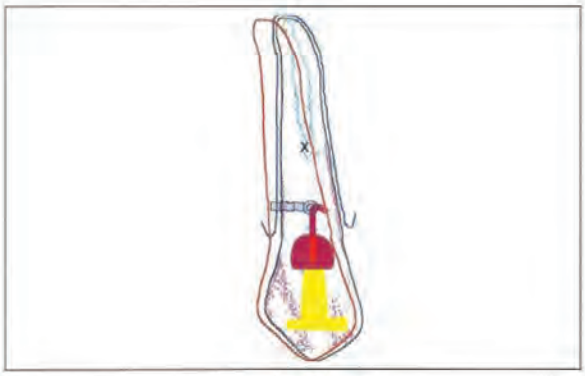


FIG 22-21 Proper planning and addition of a power arm auxiliary should allow the ability to effectively parallel roots.

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FIG 22-22 Power arms fabricated out of .020 SS round wire bonded with composite. NiTi coil springs are attached to apply force to the power arm.



FIG 22-23 Attempt at manufactured power arms on orthodontic bonding bases. This was ineffective because the length of the power arm was insufficient to move the point of force application adequately to achieve the desired results.

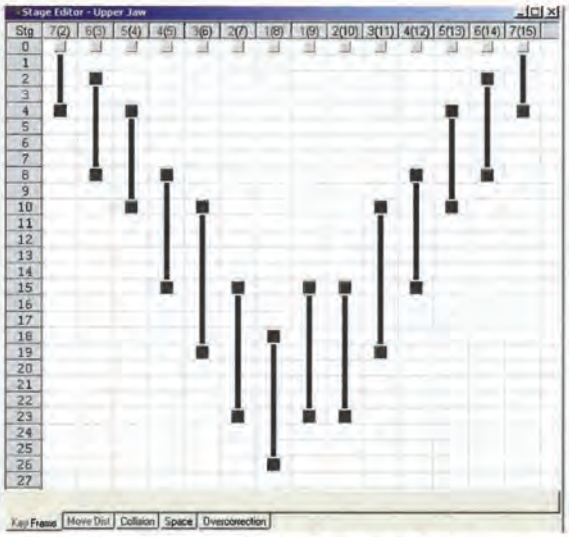


FIG 22-24 Staging diagram. The numbers across the top represent different teeth, and the vertical axis represents the aligner number. The vertical black bars in the diagram indicate the timing and rate of tooth movement. Each aligner number represents one stage.

Staging

Another aspect of proper control of tooth movement is staging. Staging is the sequence and speed that teeth are moved with aligners (Fig 22-24). Although most movements have default staging plans, the orthodontist can request custom staging when necessary. For more complex movements like extraction cases, a custom staging request is almost always required.

Planned rate of tooth motion per stage or aligner must not exceed the ability of the roots to keep up with desired movement. Proper staging is critical to effective space closure with aligners. It is usually necessary to reduce the rate of space closure with aligners to approximately one half that possible with fixed appliances. Even that rate may exceed the aligner's ability to provide the proper force system needed for root parallelism.

Clinical Issues

It should be obvious after reviewing the biomechanics of space closure with aligners that several variables combine to either produce acceptable desired results or unacceptable, undesired, and aberrant tooth movements. These are reviewed with reference to space closure and control of root position.

Foremost is the clinical crown length. The longer the clinical crown, the more likely it is that a sufficient couple can be created. Patients with very short clinical crowns are not good candidates to attempt extraction treatment with Invisalign. Single mandibular central incisor extraction tends to be successful because of the length of the clinical crowns relative to the forces applied (Figs 22-25a and 22-25b). Although root position of canines has been successfully maintained during retraction, the molars, especially maxillary molars, tend to tip mesially. This is frequently referred to as "dumping" (Figs 22-26a to 22-26c). Dumping occurs even when the molars are simply being used as anchorage for anterior retraction; this may be caused by the disadvantageous crown-to-root ratio combined with the large root surface area over which forces are distributed. Work is currently being done with various accentuated attachment designs, but as yet the ability to predictably avoid molar dumping has not been demonstrated.

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FIG 22-25 Pretreatment (*a*) and posttreatment (*b*) views of a mandibular central incisor extraction case treated with Invisalign.

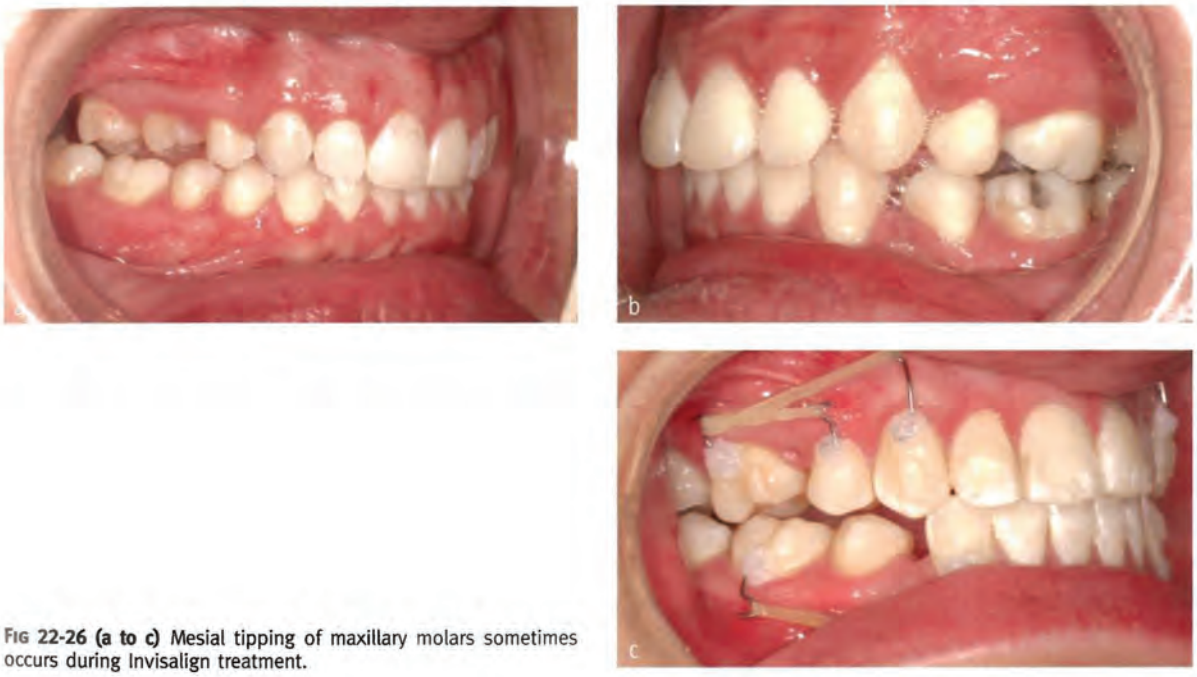


FIG 22-26 (a to c) Mesial tipping of maxillary molars sometimes occurs during Invisalign treatment.

Conclusion

With aligners, it is still difficult to achieve extraction treatment and subsequent space closure with proper tip and torque to produce root parallelism and esthetic crown inclination. Understanding the biomechanics of tooth movement with aligners and applying that knowledge to treatment planning and clinical execution should result in breakthroughs in the near future that will make such treatments more predictable and routine.

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chapter 23

Force Application with Invisalign: Constancy and Compliance

by
Trang Duong, DDS and Robert Tricca, PhD

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Duration of Force and Force Magnitude

Force duration and magnitude are important factors in tooth movement. Traditionally, it was believed that light, continuous forces applied 24 hours per day produce the most efficient tooth movement. It has been shown, however, that teeth can be successfully moved with shorter durations of force application; reportedly, the effective force application threshold is approximately 6 hours (Fig 23-1).[1]

Interrupted forces have been shown to produce tooth movement similar to that achieved with continuous force application, but with less damage to the structures of the periodontal ligament (PDL).[2] The response of periodontal tissues to orthodontic forces is discussed in detail in chapter 19. It will suffice to review here concepts of force magnitude and duration.

It is generally known that force magnitude, as well as force duration, plays an important role in producing optimal tooth movement. The ideal force magnitude is one that remains constant regardless of how the tooth moves in response. Unfortunately, force decay is inevitable after the tooth has moved a short distance (Fig 23-2). Even with the new nickel titanium and copper nitinol wires, forces decay as the teeth move.

Orthodontic force duration may be classified into three categories. The first is *continuous force*, which is a force maintained, at some fraction of the original, over time. The second category of orthodontic force duration is *interrupted force*, which describes a force level that falls to zero between activations (Fig 23-3). *Intermittent* force levels fall to zero when the appliance is removed or when a fixed appliance is temporarily deactivated.[1] The aligners worn by patients produce intermittent forces because the force is removed once the appliance is removed. Recent studies have shown that light, short-term or cyclic force applications can produce tooth movement that is comparable to that produced by light, continuous forces. Events associated with tooth movement, such as bone turnover, have been shown to continue for an indeterminate period after force decay or appliance removal. Theoretically, if a patient wears the aligners for 16 to 20 hours per day, clinically effective tooth movement will occur.

Oppenheim suggested that intermittent force was suitable for optimal tooth movement of monkey incisors, because the rest period allowed for reconstruction of the periodontal tissues (Fig 23-4).[3] In theory, light, continuous forces produce the most efficient tooth movement. Despite the best efforts to keep forces light enough to produce only frontal resorption, however, undermining resorption probably occurs in every patient.

Clinical experience with fixed appliances has shown that a 4- to 6-week appointment cycle is usually sufficient to track the length of activation. With the newest generation of memory archwires and self-ligating brackets, 8-week activations have been used. An appliance activated too frequently can inhibit the biologic repair process of the tooth and cause damage to the teeth.

Wear Time with Invisalign

When Invisalign was introduced, the optimum reactivation schedule (ie, the amount of time each aligner should be worn before advancing to the next aligner) was unknown. It was assumed, however, that over time as the aligners were worn, the magnitude of applied force would diminish (see Fig 23-4). This could be a consequence of material fatigue and the distance the teeth had moved. To understand the outcomes of forces applied to teeth under varying conditions, a randomized clinical trial was conducted at the University of Washington.[4] The objective was to specifically determine the activation time and optimal frequency of appliance change with Invisalign. This study also examined the optimal material stiffness.

The inclusion criteria for this study were that the patient must be over 18 years of age and have the ability to attend weekly appointments. Patients requiring orthognathic surgery were excluded from the study. After enrollment, consent, and collection of orthodontic records, four clinical investigators independently planned treatment for each patient. At least three of the four orthodontists had to agree on a particular plan before it was chosen.

Based on the severity of the malocclusion and the treatment plan, patients were placed in the extraction or nonextraction and high versus low peer-assessment rating (PAR) stratification. The extraction group consisted of either mandibular incisor or premolar extractions. Patients were then randomly assigned to one of four groups: hard or soft plastic, and 1- or 2-week schedule for appliance change. The hard material was twice as stiff as the commercial material; the soft material was one-tenth as stiff as the commercial material. The sample consisted of 51 patients with a mean age of 34 years (range: 19 to 55 years). There were no significant differences among the four groups in terms of age, gender, or race.

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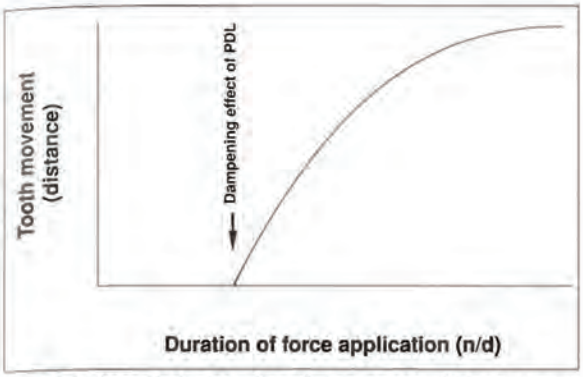


FIG 23-1 Theoretical plot of tooth movement efficiency versus duration of force. Successful tooth movement can be produced by shorter durations, with a threshold (periodontal ligament [PDL] dampening) at about 6 hours.

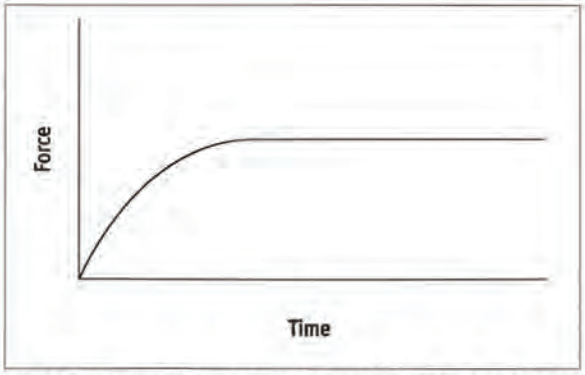


FIG 23-2 Diagram of force decay in an ideal spring situation. An ideal spring would maintain the same amount of force regardless of the distance a tooth moved. With any type of wire (or spring or aligner material), however, force decays as the tooth moves.

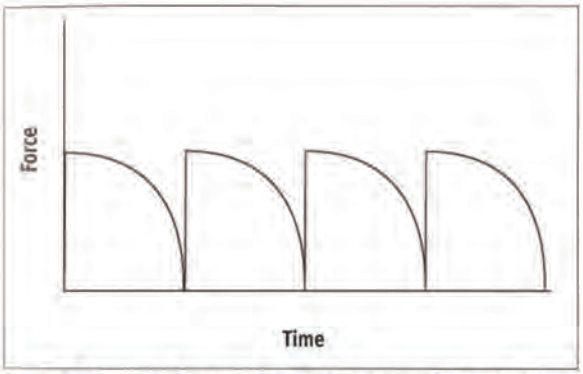


FIG 23-3 Diagram of interrupted forces. Interrupted forces drop to zero between activations.

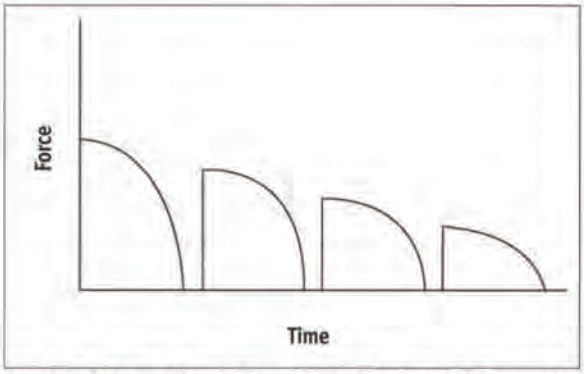


FIG 23-4 Diagram of intermittent force. This occurs in removable appliances when the force drops to zero when the appliance is taken out. The force resumes when the appliance is replaced. Forces with Invisalign would most resemble this type of diagram.

Although there were no statistically significant findings, some trends were observed. The patients who wore their aligners for 2-week intervals had a greater tendency to have completed the initial series of aligners than did patients in the 1-week groups (21% versus 37%, $P < .20$).[4] Of the four treatment protocols, the 2-week hard material group showed the best results in all measurements of occlusal and alignment improvement. This trend was seen for every index. It is possible that the lack of statistical significance is attributable to a lack of power in the study due to its small sample size. The difference between the 1- and 2-week groups might have been much larger and found to be statistically significant if the sample size were doubled.

This clinical trial concluded that the 2-week activation times achieved a higher degree of success than 1-week activation times. Subjects with a 2-week activation regimen, no extractions, and a low PAR score were more likely to complete their initial series of aligners. This study supports Align Technology's current recommendation of a 2-week wear time for each aligner.

Based on the results of this study, the optimal wear time per aligner is 2 weeks for approximately 16 to 20 hours per day. Tooth movement, however, is a complex phenomenon. Individual responses vary from patient to patient, tooth to tooth, and depending on the type of tooth movement. It is recommended, therefore, that each aligner be completely passive prior to progressing to the next aligner. Patients have been recommended to wear their aligners for 3 weeks if the teeth have not moved to the desired position after 2 weeks. For optimal progress and results, the clinician must monitor individual tooth movements and refer back to the ClinCheck at each appointment to ensure that the actual movements of the teeth match those from the programmed treatment.

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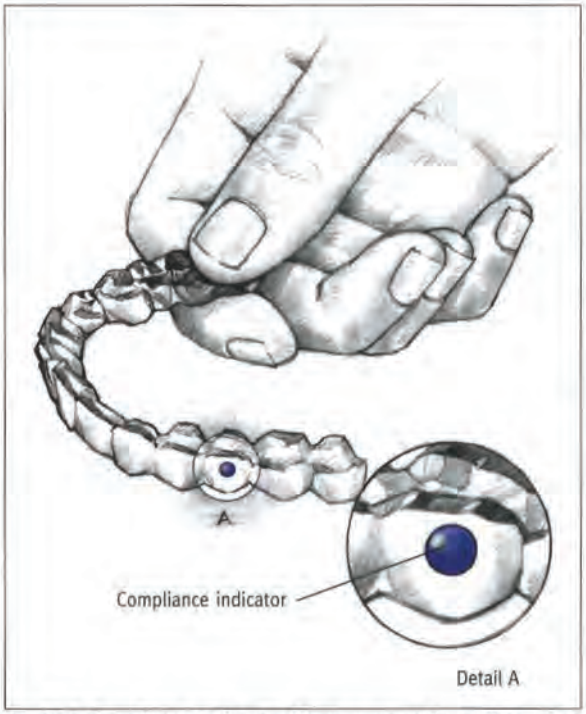


Fig 23-5 Compliance indicator (A) on a posterior surface of an aligner.

The Invisalign System is most effective when the patient wears the aligners as prescribed by the orthodontist. In fact, just about any orthodontist would freely state, "Give me a good cooperator, and I'll treat anything." Clearly, patient cooperation is vitally important for a successful outcome—not only with fixed appliances, but also with the Invisalign System. Extended removal of the aligner for any reason beyond what is recommended interrupts the treatment plan and lengthens the overall period of treatment. If the distance between each interval were to be increased, the expected outcome would be very little and unpredictable tooth movement.

Compliance with aligner wear during the course of Invisalign treatment is solely the responsibility of the patient. Reminders are a helpful method to aid patient cooperation. The orthodontist can objectively assess patient cooperation through the use of compliance indicators. Compliance indicators are mounted on each aligner (Fig 23-5) and are designed to give a visual indication as to how long a patient has been wearing the aligner. Some advantages of compliance indicators include the following:

- Better data for communicating aligner compliance with patients, including increased patient knowledge and recall of usage, increased compliance in wearing the dental appliance, and increased patient satisfaction as a result.
- A means of self-monitoring for the patient.
- Reduction of the patient's anxiety levels without requiring oral or written instructions. Because appliance usage is self-evident, there are no instructions to read or clocks to watch on the part of the patient.
- Better information for the orthodontist on patient progress during the treatment.

A compliance indicator with a layered-disk technology is shown in Fig 23-6. Interaction with oral fluids such as saliva causes a visual change (eg, color, mass, shape) in the indicator. Changes in an indicator occur as aligner wear time increases. The layered disk is composed of an active

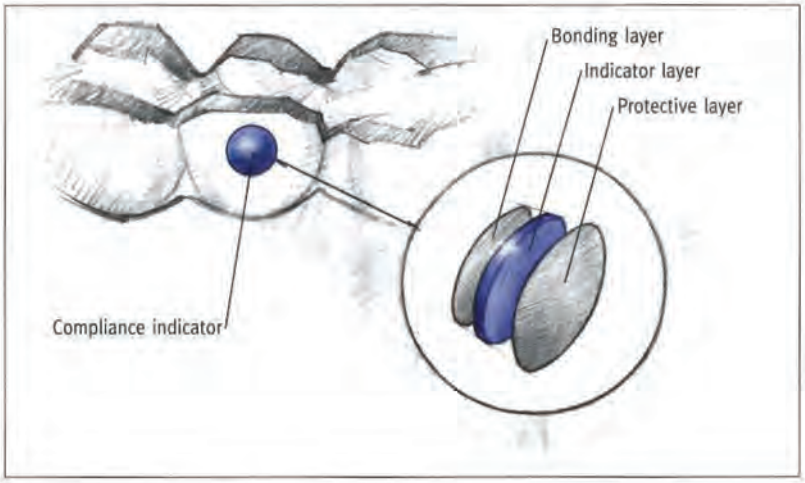


Fig 23-6 Compliance indicator with layered-disk technology.

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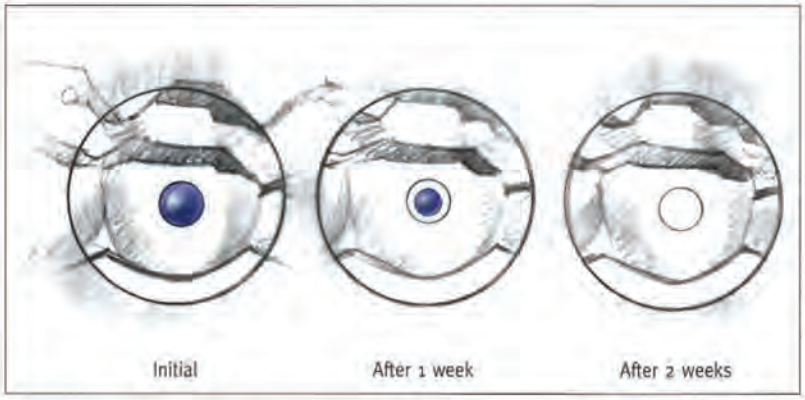


Fig 23-7 Compliance indicator over time corresponding with good aligner wear.

indicator layer, a protective layer, and a bonding layer. The protective layer is a thin, transparent film that protects the indicator layer from toothbrushing, buccal or lingual contact, and other external forces. The indicator layer can be composed of a water-soluble polymer and a pigment. Interaction with saliva and other oral fluids slowly dissolves the polymer and reduces the size of the indicator layer. For example, after 1 week with good compliance, the indicator may lose half its mass. After 2 weeks of good compliance, the indicator layer may be completely dissolved (Fig 23-7). The third layer of the compliance indicator is a bonding layer that is used to adhere the indicator layer to the aligner surface. The bonding layer can be composed of a biocompatible pressure-sensitive adhesive.

A compliance indicator on aligners provides a better understanding of patient compliance and aids in improving the clinical outcome for patients treated with the Invisalign System. It is best that the clinician prescribe 300 to 400 hours of aligner wear time. No harm can be done by wearing the aligners too long, but many problems are possible if the aligners are not worn constantly and long enough.

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SECTION IV

CLINICAL CONSIDERATIONS IN USING THE INVISALIGN SYSTEM

chapter 24

ADVANTAGES OF THE INVISALIGN SYSTEM

by
Trang Duong, DDS and Mitra Derakhshan, DDS

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The First Appliances

Edward Angle is not only the father of modern orthodontics, he was also known to be a prolific inventor of orthodontic appliances. His first appliance was the E-arch. The E-arch was developed in the late 1800s and consisted of bands placed on the teeth with ligatures to the heavy archwire (Fig 24-1a). The pin and tube, which permitted precise torque and tip control to be accomplished by using a vertical tube on each tooth with a soldered pin on the base archwire, came next (Fig 24-1b). This appliance was impractical because of the time and effort required to activate it. The next appliance Angle developed was the ribbon arch. It incorporated a vertical rectangular slot behind the tube (Fig 24-1c). A ribbon arch consisted of gold wire and was placed into the slot and held in with pins. This appliance, unfortunately, could not torque the roots. The slot was then rotated 90 degrees and termed "edgewise" (Fig 24-1d). By changing the orientation, Angle was able to control crown and root position in all three planes of space. Just about all fixed appliances used today are based on Angle's designs.

Appliances Used Today

The appliances used today have evolved since Angle's edgewise appliance in the early 20th century. Numerous advances in cements, materials, techniques, and technology have allowed orthodontics to become more efficient, comfortable, and esthetically pleasing for the patient. In 1970, fewer than 5% of all orthodontic patients were age 18 years or older. Most of the growth of orthodontics in the 1980s was in the adult patient group. By 1990, adults consisted of approximately 25% of all orthodontic

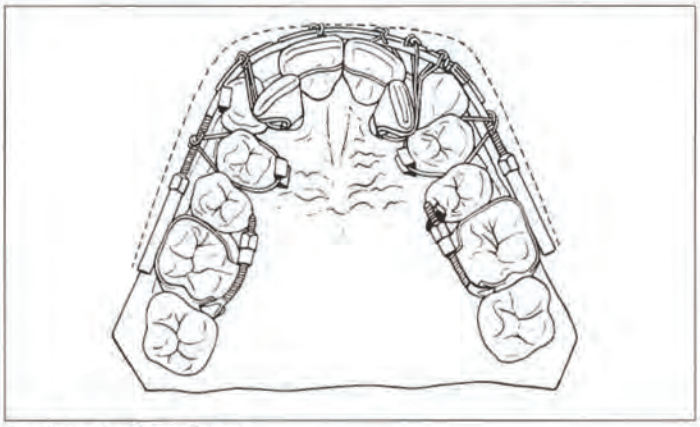


Fig 24-1a E-arch appliance.

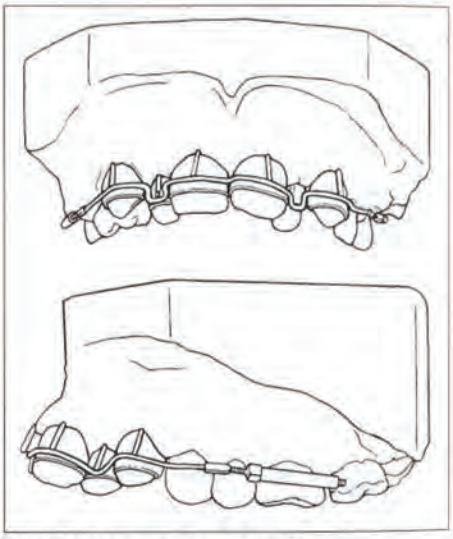


Fig 24-1b Pin and tube appliance.

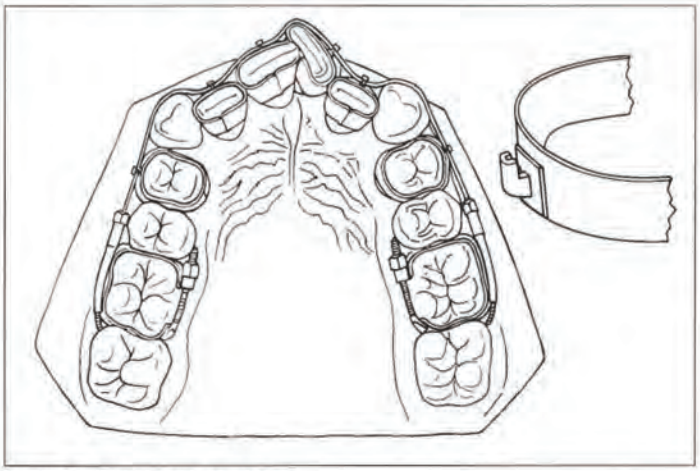


Fig 24-1c Ribbon arch appliance.



Fig 24-1d Edgewise appliance.

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patients. This trend is related to the increase in the number of orthodontic patients aged 40 and older.[1]

Most adults express some concern about the appearance of orthodontic appliances. Today, there is a high demand for an esthetic orthodontic appliance. With the introduction of bonding in the 1970s, it was possible to place fixed attachments on the lingual surface of the teeth and produce an invisible fixed appliance. The small interbracket distance and the access, unfortunately, makes the use of lingual appliances difficult and time-consuming. In addition, the discomfort level on the tongue was significant and often intolerable. With the development of ceramic brackets in the late 1980s, another esthetic option for patients seeking orthodontic treatment became available. The ceramic bracket, however, still involved a bracket bonded onto the tooth and a metal archwire. Although esthetics was greatly improved over that of metal brackets, the orthodontic wire was still visible. Invisalign offers the advantages of superior esthetics and comfort as compared to all other appliances currently available.

Esthetics

There are numerous advantages of the Invisalign System. The main benefits are that the Invisalign aligners are clear, comfortable, and removable. Because aligners are clear, they are undetectable from a distance of at least 2 feet. Many adults and teenagers want their teeth straightened but are unwilling to wear a full set of conventional fixed appliances because of esthetic concerns. Like ceramic and plastic brackets, Invisalign is an esthetic alternative for straightening teeth: the difference is that aligners are removable. And because they are undetectable, patients can wear them during important personal or business matters. Invisalign is the most esthetic option (Figs 24-2a to 24-2e).

Removability

Aligners are removable. This allows patients to maintain their current oral hygiene practices. Patients can brush and floss normally, unfettered by brackets or wires. Also, patients do not need to change their diet or eating habits; they can eat or drink whatever they please with no fear of food sticking to or breaking their appliances. Patients can also remove their aligners for special occasions such as dinner parties.

Comfort

Aligners are comfortable and do not cause irritation to the cheeks or surrounding tissues, as can happen with wires or brackets. There is no need to dispense wax or provide patients with plastic sleeves to place over the appliances because there are no bulky brackets or wires.

Bonding to Enamel Defects

Invisalign can be used with patients for whom conventional fixed appliances are contraindicated because of metal or nickel allergies or the inability to bond appliances to teeth (as in cases of amelogenesis imperfecta). These types of cases present with hypocalcified enamel, which makes bonding to the teeth difficult (Figs 24-3a and 24-3b).

No Reported Root Resorption

There have been no reported cases in which a patient treated with Invisalign showed evidence of root resorption. Invisalign offers precisely controlled movements that can be specified by the treating clinician. Tooth movements can be reduced per aligner as requested by the clinician. Studies conducted at the University of the Pacific and the University of Florida have not shown any evidence of root resorption with the Invisalign appliance.[2] Based on the current University of Florida attachment study, which has 99 patients enrolled, there has been no incidence of root resorption.[2]

Less Discomfort and Pain

Adults who have had fixed appliances as adolescents and Invisalign treatment as adults have reported that treatment with Invisalign is more comfortable and induces less pain. Invisalign treatment is unique in that the treating clinician can specify to slow down movements programmed into each aligner in patients who have a lower pain threshold. The University of Florida conducted a study in which the treatment effects of Invisalign and fixed appliance therapy were compared during the initial week of treatment. The patients were asked to complete a questionnaire for the first 7 days. Patients treated with

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FIG 24-2 Comparison of the esthetics of orthodontic appliances: (*a*) metal brackets, (*b*) self-ligating brackets, (*c*) clear brackets, (*d*) lingual brackets, (*e*) Invisalign.

Invisalign reported less negative effects on their overall quality of life during the initial week. They also reported less pain from day 2 through day 7.[2]

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FIG 24-3a Amelogenesis imperfecta.



FIG 24-3b Amelogenesis treatment progress with Invisalign aligners in place.



FIG 24-4a Decalcification associated with poor oral hygiene during fixed appliance therapy.



FIG 24-4b Poor oral hygiene during fixed appliance therapy causing gingivitis.

Hygiene

Oral hygiene is easier and better to maintain during Invisalign treatment than with fixed appliances. Because the Invisalign appliance is removable, it presents no obstacle to good oral hygiene, and thus poor hygiene with Invisalign is minimal. Brushing tools such as proxy brushes and floss threaders are not necessary. Adults who have had previous periodontal disease but are in good periodontal health have more difficulty maintaining good hygiene habits, especially during fixed appliance treatment. With Invisalign, these patients do well. A study has shown that there is an improvement in gingival health during treatment with Invisalign.[3] It is commonly known that decalcification (permanent markings), decay, or periodontal disease can occur if patients do not brush their teeth properly and thoroughly during fixed appliance treatment (Figs 24-4a and 24-4b). Patients treated with Invisalign have shown to have a lower incidence of decalcification or decay compared with those treated with fixed appliances.

Numerous Restorations or Crowns

Bonding brackets onto teeth that have crowns and restorations can be challenging. Although products such as hydrofluoric acid and porcelain primer can be used to bond onto crowns, the technique requires an extra step and is not predictable. In addition, using hydrofluoric acid requires the use of a rubber dam for safety because of its highly caustic effect on tissues. Treatment with Invisalign in these types of cases is ideal because the treating clinician can specify which teeth will not have attachments and therefore reduce or eliminate this challenge (Figs 24-5a and 24-5b).

Speech

The Invisalign appliance, since it does not cover the palate, does not affect speech. In contrast, Hawley retainers or quad-helix appliances are obtrusive and can affect speech and irritate the tongue (Figs 24-6a and 24-6b).

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Fig 24-5 (a and b) Bonding is not an issue with patients who have numerous crown restorations.

Chair Time

With Invisalign, more of the clinician's time is invested up front for treatment planning with the use of ClinCheck. The advantage is that this time does not directly affect patient chair time. The chair time needed to monitor Invisalign patients is reduced. Treatment with Invisalign involves fewer instruments and inventory than treatment with fixed appliances (Figs 24-7a and 24-7b). There is no need for bands, wires, or brackets. Valuable chair time spent untying and tying A-lastics or C-chains is eliminated. All of the instruments and setup required for fixed appliances is eliminated. Office visits for patients undergoing Invisalign treatment involve the next set of aligners, a mirror, floss, and stripping instruments if interproximal reduction is part of the treatment plan. More staff time is spent on building patient relationships, which adds value to the practice. There is less armamentarium needed for each appointment. No large inventory of pliers is required, unless IPR is needed at the appointment.

Vertical Control

Invisalign has proved to be effective in controlling anterior open bite or shallow overbite. Unlike conventional fixed appliances, with which open bites can easily occur during the initial leveling stages, Invisalign treatment has been found to reduce this tendency. Because aligners cover the entire occlusal surface of the posterior teeth, they have a posterior bite block effect and as a result are excellent at controlling anterior open bites and open-bite tendencies (Figs 24-8a to 24-8c).



Fig 24-6a Hawley appliance covering palate.



Fig 24-6b Quad-helix appliance covering palate.

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FIG 24-7a Basic instrument setup with fixed appliances.



FIG 24-7b Basic instrument setup with Invisalign.

Treatment in Deep Bite Cases

Malocclusions with a deep overbite can be treated immediately in both arches and do not require bite planes or posterior bite blocks.



FIG 24-8a Initial photograph of an anterior open bite.

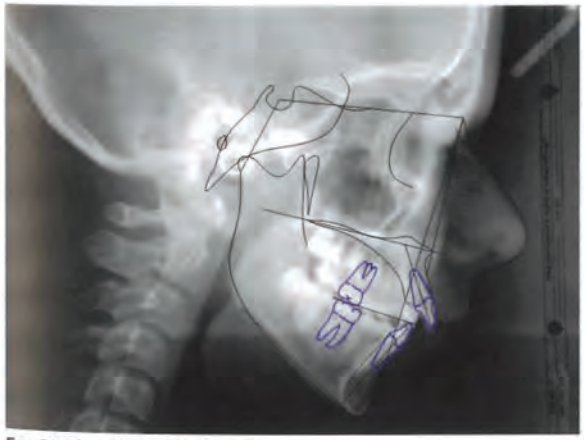


FIG 24-8b Initial cephalogram.

Fewer Emergencies

Emergencies with Invisalign treatment are fewer than with fixed appliances. There is no potential for broken brackets or protruding wires. Occasionally, there are instances where the patient loses an aligner or an aligner breaks, but neither situation requires immediate attention. For these situations, the patient can be seen the following day to arrange for a replacement aligner to be sent. More practically, depending on the timing, the patient may be able to simply advance to the next aligner. If this is not possible, the patient is usually advised to wear the previous aligner until the replacement arrives, which typically takes a few days. In some instances, the aligners may go off track, ie, they may no longer fit and the teeth are not moving to the desired positions. When this happens, the patient can call the doctor to schedule an appointment—this, too, is not an emergency.



FIG 24-8c Progress: control of overbite.

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Control of Individual Tooth Movements

Invisalign is unique in that the clinician can specify exactly which teeth are to be moved and which are to remain stable during treatment. With this option, for example, teeth with preexisting root resorption or fixed partial dentures can be programmed to remain stable during treatment.

Phase 2 Treatment

Invisalign treatment is recommended for patients that have a fully erupted dentition from second molar to second molar. A study of Invisalign treatment in adolescents showed that treatment in patients 12 to 18 years of age with a fully erupted dentition was effective (see chapter 29). When a patient has had phase 1 treatment during the mixed dentition to correct either habits, jaw discrepancies, or major alignment, by phase 2, he or she is usually tired of fixed appliance therapy. Invisalign can be used during phase 2 treatment once the permanent dentition is fully erupted. This provides a good change for the patient, as well as a great esthetic treatment at a time when physical appearance and social acceptance are of heightened importance.

Control of Bruxism

One advantage of aligner use in patients who suffer from bruxism or clenching habits is that the occlusal coverage acts as a protective barrier on the teeth. Therefore, during orthodontic treatment, there can be a reduction of wear facets that may occur from bruxism habits.

Special Patient Populations

Because of the removability and comfort of the aligner, Invisalign is the treatment of choice for athletes and patients who play instruments. The treatment does not interfere with the daily routine of an athlete or musician: they can always remove their aligners, when necessary, to compete or perform. Especially for athletes, the safety aspect of not having to worry about brackets breaking or irritation during sports is crucial. If an aligner is left in during sports, in a sense it acts as a mouth guard.

Bleaching During Treatment

An additional benefit is that, concurrent with Invisalign treatment, tooth bleaching can be administered. Thus, Invisalign can offer a full package of esthetic treatments.

ClinCheck as a Diagnostic Tool

One significant advantage of Invisalign treatment is the three-dimensional visualization of the treatment plan provided through ClinCheck. ClinCheck provides the first opportunity for the clinician to view the treatment from beginning to end before initiating treatment (see chapter 11).

Conclusion

Invisalign treatment offers patients a wide variety of advantages. Not only is Invisalign the most esthetically pleasing appliance available today, but it also can make orthodontic treatment more comfortable and convenient. Today, with the increasing development and use of digital and computer technology, a new generation of orthodontists is being developed. These orthodontists have the knowledge of the concepts and use of traditional fixed appliances, but are also schooled in the new technological tools that are available today. Those who can incorporate their scientific knowledge with technology and learn how to properly use them will have a distinct advantage in orthodontics today and in the future.

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chapter 25

REVIEW OF THE DIAGNOSTIC PROCESS

by
Robert L. Boyd, DDS

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Just about all potential Invisalign patients require detailed explanation. They have seen the advertisements, talked to their dentists, or thoroughly explored the Invisalign website. But because orthodontic treatment has traditionally been associated with fixed appliances, patients may still believe that it is painful and that they have to come for appointments every month; most significantly, they may have the mindset that Invisalign treatment is faster.

Also, it is wrong to think that patients with certain malocclusions are better candidates for Invisalign treatment; but then, there are patients who can only be treated using fixed appliances. The importance of patient education cannot be overemphasized. Initially, it is best to have the treatment coordinator talk to the patient and explain what the Invisalign System is, how it works, and how important cooperation and compliance are for a successful outcome. This session with the patient, therefore, serves as an opportunity for the clinician to address mistaken impressions and to provide realistic expectations and understanding about orthodontic treatment. Specifically, it must be emphasized that Invisalign trays are not magical instruments that can correct everything. The patient has to realize that the process is painless, but that all the elements of the biology of tooth movement are still in effect.

The most important person in the patient-education process is the clinician. A focused question-and-answer conversation with the patient is critical. Obviously, the clinician must be well informed about Invisalign System appliance characteristics. This chapter provides an overview of a system that can be used to examine a patient and formulate a tentative treatment plan. A series of case reports is also presented to illustrate the potential of Invisalign treatment.

Initial Consultation

All prospective patients should be provided information about Invisalign treatment prior to their initial visit. This can be done by sending information about Invisalign with the initial health history (brochures are available from Align Technology), having the patient visit the Invisalign website, or developing your own website with this information.

Any staff member who comes in contact with the patient needs to be knowledgeable about the Invisalign System and ready to answer questions. This requires training that focuses on Invisalign treatment. The treatment coordinator should convey pertinent information about this patient and his or her concerns to the clinician before the clinician meets the patient.

Patients should be seated fully upright when introduced to the clinician. When initially speaking with the patient, the clinician should try to discover areas of mutual interest by asking patients about their own interests. The clinician should listen to the patient carefully rather than immediately respond or express opinions. A question-and-answer conversational style generally yields more meaningful information.

Clinical Examination

The following suggestions do not differ substantially from the general format followed for clinical examinations. After listening carefully to the patient's concerns, the clinician should determine the patient's true hopes and expectations for the treatment. The clinician should also determine if there are medical contraindications to treatment by carefully examining the medical history and asking follow-up questions where needed for additional information.

Then the clinician should ask the patient if it is agreeable to begin the initial clinical examination. The first thing to do is determine the patient's chief concern (eg, "crooked front teeth") in relation to his or her overall esthetic appearance. A good question to ask is, "What would you like to change about the way your teeth look?" and a follow-up question, "Are you satisfied with the color and shapes of your teeth?" Then the clinical exam starts with recording all relevant findings, preferably with an assistant taking notes as the clinician examines the patient. Things to note are:

The skeletal pattern (Class I, II, or III): This should be specific for explaining what skeletal proportion is not ideal. For example, a patient could have a retrognathic mandible or a protrusive maxilla.

Degree of lip competence: Lip length and thickness, and the way the lips relate to the nose and chin should be noted.

Symmetry: Are the dental midlines on? The middle of the philtrum should be used as a reference for the midline. The direction and amount (in millimeters) of deviation, if any, should be documented for both the maxillary and mandibular arch. If it is more than 2 mm, ask the patient if they have ever noticed this.

Analysis of the smile: The percentage of tooth display in speaking and full smile should be recorded. Does the

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lower lip follow the contour of the maxillary arch? Is the smile symmetric? Do the buccal corridors display excess space? Are the teeth as white as the patient wishes?

Analysis of the profile: Is the smile straight, convex, or concave from the side view? Are facial proportions balanced?

Frontal analysis: Deviation of the nose, alar base width, and chin deviation (which side and how many millimeters) should be noted. If noticeable asymmetries of the chin or nose are present, ask the patient, "Is there anything you would want to change about the way you look?" Avoid referring to any specific anatomic variation unless the patient brings this up as something he or she wants to change.

Analysis of the occlusion: Angle's classification of the molars and canines, overbite, overjet, presence of a cant of the occlusal plane, missing teeth, large restorations, and crossbites (anterior or posterior) should all be recorded. The clinician should also note whether centric relation is coincident with centric occlusion. If they are different, the degree (in millimeters) and direction of the mandibular movement should be recorded.

TMJ status: At the very least, maximum opening, jaw opening deviations, clicking and creptitus, muscle soreness on palpation, and history of pain must be established.

Periodontal status: The patient's ability to remove plaque and areas of poor plaque removal should be noted. Color variations, including red, edematous gingiva, should be recorded. The clinician should look for areas of thin gingiva (minimal attached gingiva) and gingival recession (especially in relation to labially prominent teeth), high frenum attachments, or gingival discolorations from amalgam or pigment. If all tissues appear healthy, at least all molars should be probed for increased pocket depth (greater than 3 mm) or bleeding upon gentle probing. All other areas of red or inflamed gingiva should be spot probed.

Decision About Treatment Feasibility

The primary conclusion that needs to be determined after this initial examination is whether the patient can be effectively treated with Invisalign. As with any other orthodontic appliance, it is very important that this decision take into consideration the level of the clinician's expertise using Invisalign. Many times the clinician will have to tell the patient that additional diagnostic records (panoramic or periapical radiographs, intraoral and extraoral photographs, cephalometric evaluation, periodontal evaluation, radiographs of the temporomandibular joint, etc) are necessary to make the final diagnosis and treatment plan. The clinician may wish to e-mail the digital photographs to Align Technology for an answer about the feasibility of treatment. A response can be provided at no charge within 48 hours.

Invisalign can provide predictable treatment in the following situations:

Patients who do not want fixed appliances. Patients who had orthodontic treatment before as adolescents frequently do not want fixed appliances again. They may also be extremely focused on esthetic issues, perhaps if they have a high public visibility. Fear of pain is another reason why many patients do not want fixed appliances. Many times high-school-age (ie, 15- to 18-year-old) adolescents are strongly motivated for improved esthetics of their smile but are not interested in having fixed appliances.

Functional posterior occlusion. A patient whose only complaint is the appearance of the teeth themselves is usually a good candidate for treatment, especially if there is a stable posterior occlusion.

Patients who do not require extensive restoration of anterior teeth. Patients who need extensive restoration of anterior teeth should be presented alternatives, such as restoration of the anterior teeth, that may be able to solve their esthetic concerns without orthodontic treatment. Many times, Invisalign treatment to improve tooth positions will create a situation in which less invasive restorative dentistry can be done. The improved tooth positions will necessitate lesser amounts of tooth reduction for placement of laminate veneers.

Patients who require primarily tipping movements. If the malocclusion can be solved primarily by mild amounts of proclination or expansion, the patient is usually a very good candidate for Invisalign.

Patients who are periodontally compromised or have high caries rates. Two published studies have found that there is less plaque and gingivitis during Invisalign treatment than before treatment.[1-3] This is in contrast to other studies that show an increase in plaque and gingivitis with fixed appliances.[4,5] Patients with a high caries rate can be better managed with Invisalign than with fixed appliances because of the decreased plaque retention and increased access to interproximal areas.

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Patients who require prosthetic treatment. Coordination of prosthetic treatment is facilitated with Invisalign. The numerous trial treatments done on the ClinCheck images allow for testing the prosthetic result before the treatment actually starts. The restorative dentist can show patients virtual treatments with tooth replacements, and the patients will better understand the proposed treatment.

Patients with short roots or increased susceptibility to root resorption. A recent study showed that root resorption is not measurable with Invisalign treatment (Wheeler T, unpublished data, 2006). This is in contrast to fixed appliances, with which 10% of patients generally show clinically significant root resorption of 3 mm or more.[6]

Patients with shallow overbite or slight open bite. Because of the intrusive effect on the posterior teeth during aligner wear, overbite is usually improved by 1 to 2 mm during treatment. In contrast, fixed appliances generally have a small degree of bite opening effect on patients with edge-to-edge or slightly open bite malocclusions.[5]

Patients who have excessive wear on their teeth. Patients who grind or brux their teeth have no way to stop this problem during orthodontic treatment with fixed appliances unless they wear an appliance such as a nightguard during treatment, which is difficult for the patient to do. Invisalign creates a layer of plastic material between the teeth to prevent additional wear.

Patients with myofacial pain. Numerous studies have shown that single or double splints placed between the teeth disarticulate the teeth and decrease the effects of muscle soreness.[7] A recent study by Nedwed and Miethke[8] showed no increase in myofacial pain during Invisalign treatment.

Patients with mild Class II (end-on) malocclusion with acceptable facial esthetics and mild crowding. Use of Class II elastics and/or molar distalization of 2 to 3 mm is a predictable movement with Invisalign without opening the bite as fixed appliances frequently do. This is because molar distalization is usually associated with molar extrusion and loss of anchorage with flaring of the anterior teeth.

Patients with extensive porcelain, gold, or other restorations. Bonding and debonding procedures pose certain risk factors for these restorations and can be avoided with Invisalign.

Deep overbite. Generally with fixed appliances, a progression through initial archwires to a larger-diameter wire is necessary before significant bite opening can occur. This treatment may require 6 to 12 months, depending on the severity of the deep bite. In addition, fixed or removable bite-separating appliances may also be necessary to hold the teeth apart to prevent the occlusion from loosening fixed appliances. Wheeler (unpublished data, 2006) has shown that intrusion is one of the most predictable movements that can be achieved with Invisalign.

Anterior and posterior crossbites. For the same reason as in the case of deep overbite (clearance of tooth interferences), anterior and posterior crossbites can be more easily managed with Invisalign than fixed appliances because aligners provide disarticulation for the teeth and smooth surfaces for teeth to slide over each other without the need for bite-opening appliances.

Problem List and Treatment Goals

The next step is to formulate a problem list, which will help the clinician focus on the best solutions. This should include all of the issues that the patient presented with and the problems identified by the clinician at the initial exam.

Specific solutions to each of the problems are needed to be sure all of the problems are taken into account with the proposed treatment plan. The problem list and solutions will then serve as the basis of the treatment goals and objectives.

Treatment Plan

A sequenced step-by-step treatment plan is required to create the desired tooth movement that will fulfill the goals and objectives. This should include all other treatments such as periodontal, endodontic, restorative, and retention. Referring back to this list throughout treatment will ensure that the correct order of treatment priorities was maintained.

Treated Cases

The cases illustrated in Figs 25-1 to 25-28 show types of treatment possible with Invisalign. They are arranged in order of increasing difficulty. It is especially important to carefully analyze the face initially to determine the degree of lip support, midlines, overjet/overbite relationships, arch form, esthetics of the smile, and the areas mentioned in the beginning of this chapter. Each case includes still

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FIGS 25-1 TO 25-4 Patient 1.



FIG 25-1 (a to m) This patient presented with the chief complaint of crowded teeth. The patient was very particular about his appearance. He liked his facial appearance and balance. The dimple in his chin was important. Radiographically, there were no findings of concern. After an attentive interview session with the patient and review of records, the decision was made to procline the incisors, perform interproximal reduction, and expand the dental arches.

photos of the beginning and final stage ClinChecks that were approved for the patient. It is important to analyze each of these ClinChecks to determine how close the actual results are to the final occlusion. Unfortunately, it is not possible to show the actual movement of the teeth in this printed form. However, the actual paths of movement and staging need to be carefully analyzed for correctness of biomechanics of movement, anchorage, and final tooth position using the Superimposition tool (see chapter 14).

An informed consent form such as the one shown in Fig 25-29 will be helpful to ensure good patient cooperation and uneventful progress of treatment.

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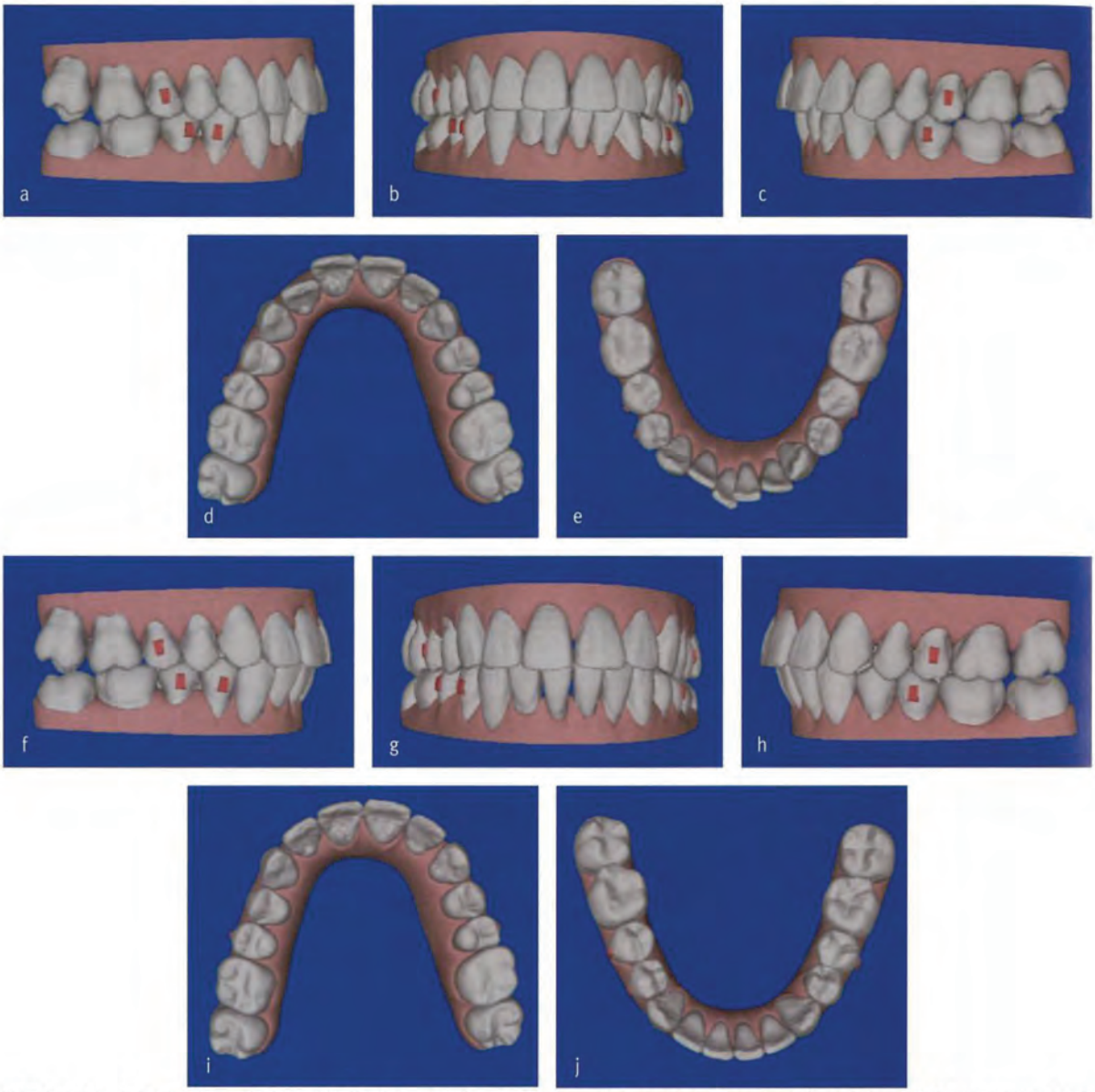


Fig 25-2 (a to j) Comparison of these ClinCheck images (*a to e*, preoperative; *f to j*, treatment goal) and the end-of-treatment records will show that the goals of treatment were achievable. Note the correction of the posterior crossbite on the right second molar.

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FIG 25-3 (a to k) The final result images display the characteristic posterior open bite. Despite this opening, however, the deep bite was improved. Note the disappearance of the canine tip and conservation of tooth morphology especially in the anterior segments. Teeth were slightly reduced mesiodistally, which helped reduce the presence of dark, open spaces interproximally (commonly referred to as "black triangles"). Also note the correction of the crossbite of the right second molars. The usual retention plan is to have the patient wear retainers full time for 4 to 6 months and then during sleep indefinitely. Patients are told retainer wear reduces tooth wear from nighttime bruxing and can also be used for periodic home bleaching. Once retainers are worn during sleep only, the slight posterior open bite closes within 4 to 6 weeks.

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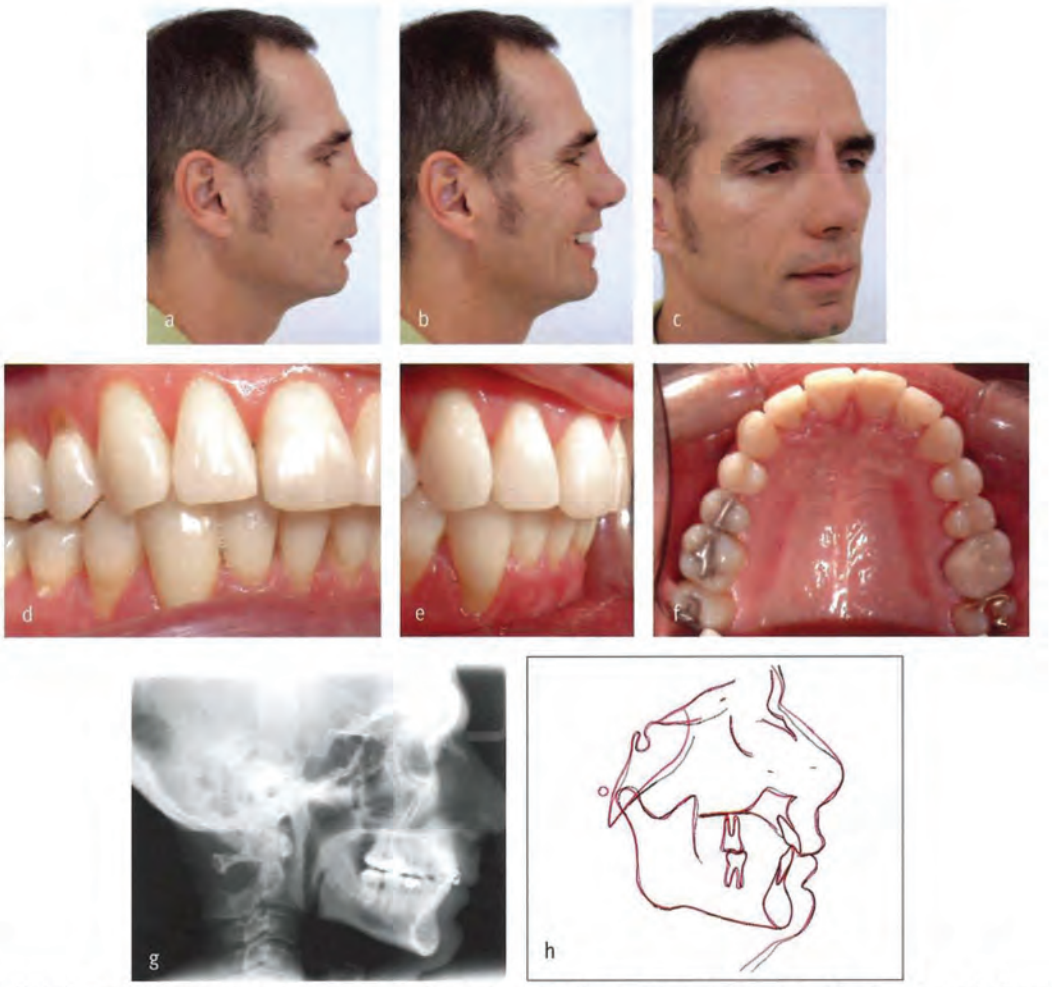


FIG 25-4 (a to h) These images depict the retention at the 3-year recall. All corrections have been stable since the end of treatment. The patient has been compliant with his retainers. Clearly, as in all cases, this patient's cooperation made a significant difference. The superimposed cephalometric tracings reveal the conservative nature of this particular treatment plan.

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FIGS 25-5 TO 25-7 Patient 2.



FIG 25-5 (a to j) This patient's chief complaint was that his teeth were "shifting" and "overlapped." The angular nature of his chin disguised the retrognathism, and the lips were competent. The position of the maxillary incisors was within esthetic norms, but his canine and molar occlusion was end-on. After working with the ClinCheck images (see Figs 25-6a to 25-6j), the decision was made not to disturb the posterior and canine occlusion, but rather open the bite, slightly expand the arches to gain more space, and eliminate the "black triangles" through interproximal reduction.

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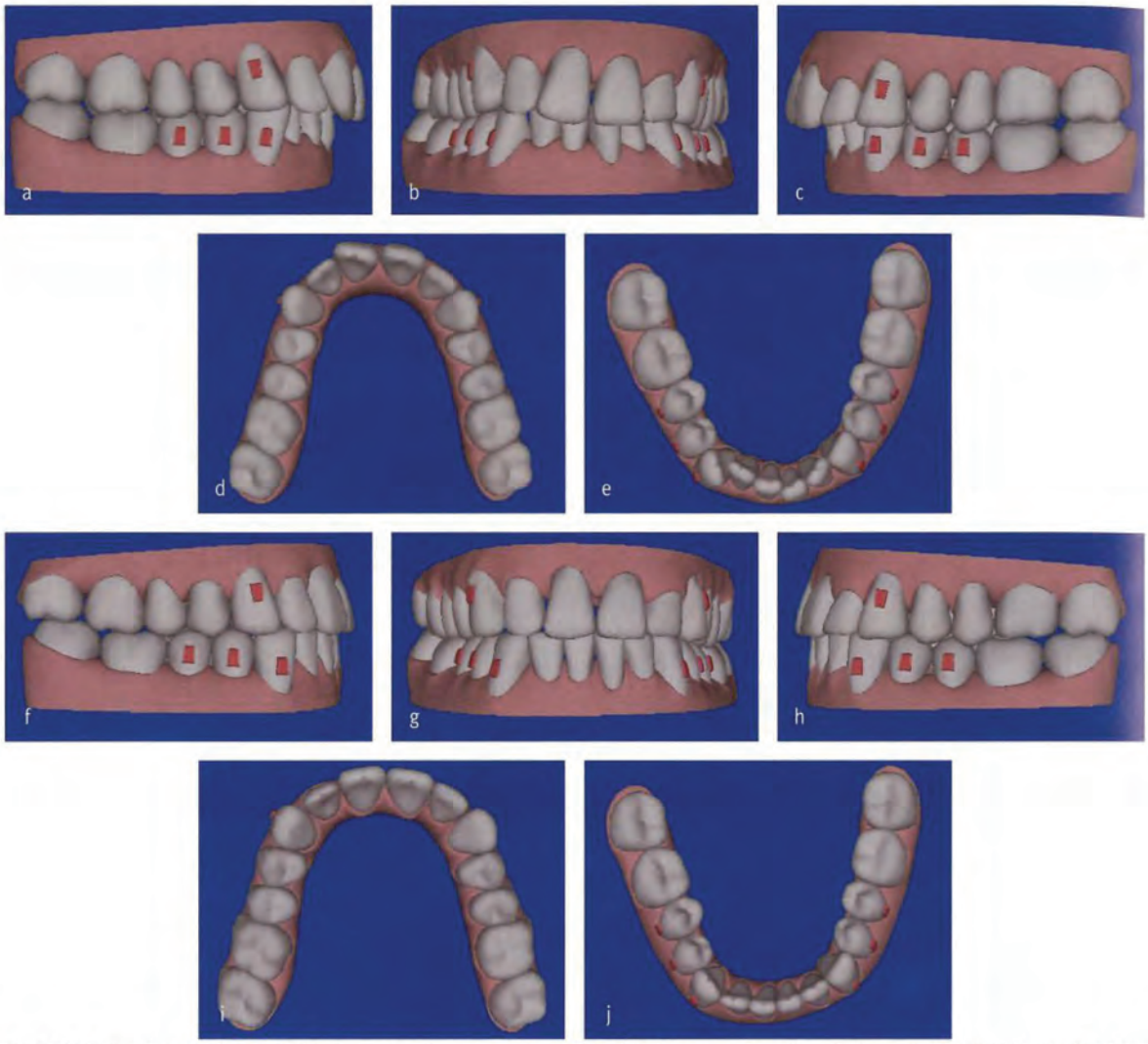


FIG 25-6 Comparison of these ClinCheck images (*a to e*, preoperative; *f to j*, treatment goal) and the end-of-treatment records show that the goals of treatment were achievable.

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FIG 25-7 (a to k) Three years after the end of active treatment, the result is stable. Note the improved tooth morphology and profile appearance. The patient also bleached his teeth with a 30% carbamide peroxide gel, using his aligners as bleaching trays. His excellent cooperation during active treatment was essential to the results and their retention.

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FIGS 25-8 TO 25-11 Patient 3.



FIG 25-8 (a to l) The chief complaint of this 53-year-old patient was the overlap of her anterior teeth. She reported a history of trauma and endodontic treatment (at age 13) on the maxillary right central incisor. She had orthodontic treatment as a teenager, and her orthodontist had informed her that this tooth was ankylosed. Facial esthetics were good, and occlusion was Class I with a moderate overbite. Radiographic examination showed extensive restorative work, but this did not contraindicate orthodontic treatment. After her previous fixed orthodontic treatment, which included extraction of the four first premolars, the patient was not compliant with her retainers and stopped wearing them shortly after receiving them. The return of crowding, however, was slow. Perhaps because it was ankylosed, the maxillary right central incisor was in an acceptable position. The patient did not want fixed appliances again and decided to have Invisalign treatment. The treatment plan was to keep the maxillary right central incisor in its current position and resolve the crowding. This approach necessitated significant interproximal reduction (IPR) and slight expansion. IPR was further necessary to eliminate the black triangles between her anterior teeth.

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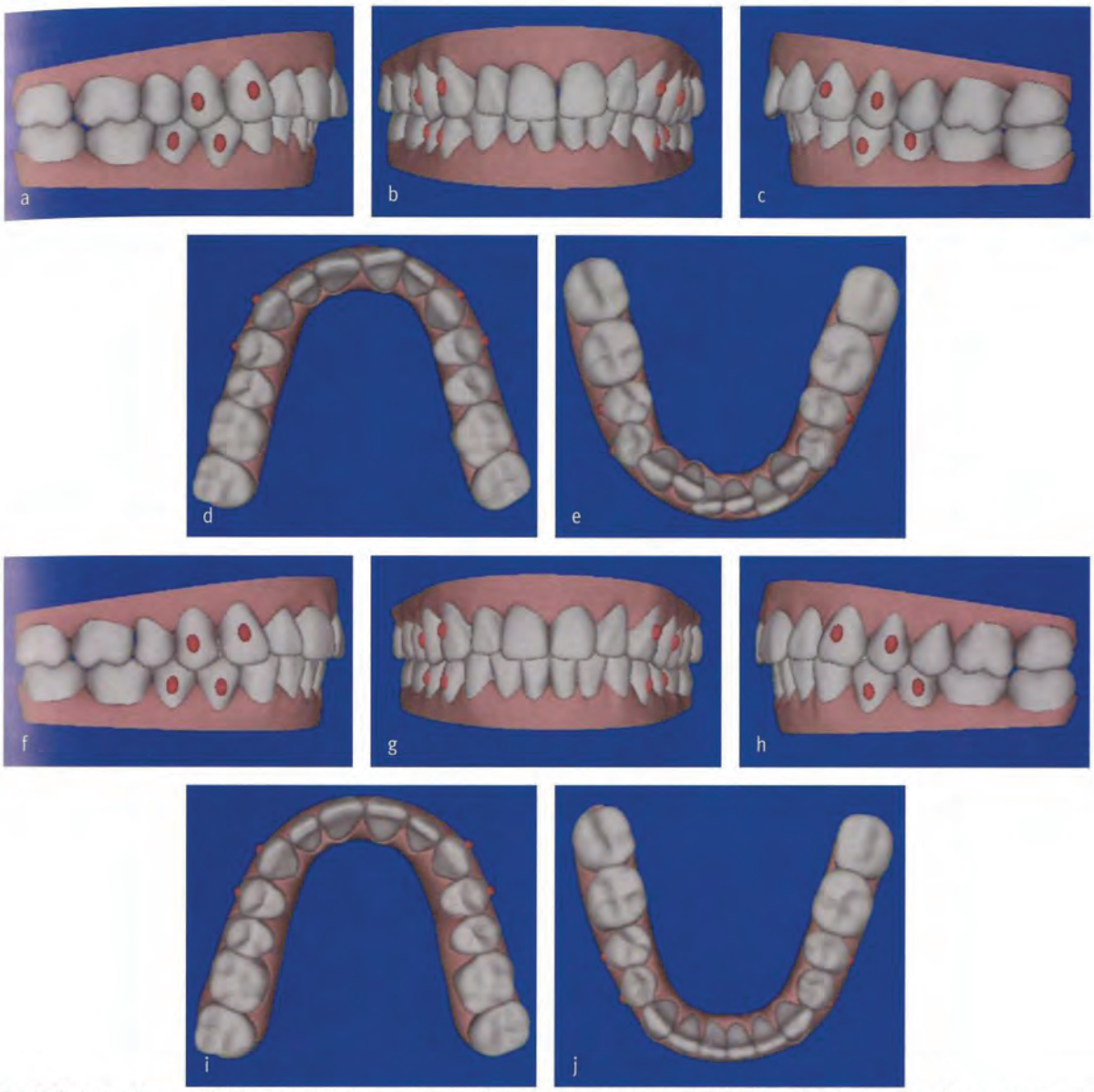


FIG 25-9 Comparison of ClinCheck images (*a to e*, preoperative; *f to j*, treatment goal) with the end-of-treatment and 3-year posttreatment images shows that the goals of treatment were achievable.

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FIG 25-10 (a to k) Posttreatment success. ClinCheck predictions have been accomplished. An esthetically pleasing smile is present. Fourteen months of Invisalign treatment, including one series of case-refinement aligners, was required to correct the crowding.

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FIG 25-11 (a to k) The 3-year posttreatment images reveal that the end result was maintained successfully. These photos indicate stability of the orthodontic treatment with nighttime wear of retainers. Note that the improvement of the gingival recession of the mandibular left central incisor was maintained without the need for an epithelial graft as initially planned.

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FIGS 25-12 TO 25-15 Patient 4.



FIG 25-12 (a to m) The chief complaint of this patient was the mandibular incisor crowding and chipped maxillary incisors. She had orthodontic treatment with first premolar extractions as a teenager. She stopped wearing her retainers shortly after removal of the appliances. The patient preferred a broader smile, so the treatment plan was to expand her arches slightly and to improve the overjet, eliminate crowding, and establish better intercuspation. An epithelial graft had been previously placed on the maxillary right canine because of gingival recession, and another graft was planned for placement on the mandibular left central incisor, which was in labioversion. Space was created with posterior arch expansion and interproximal reduction in the mandibular arch. Care was taken not to move the mandibular left central incisor labially, and instructions were given to the Invisalign computer operator at the time of the ClinCheck to have this tooth's root moved lingually to encourage coronal movement of the gingival tissue. This was successful, and the posttreatment epithelial graft was not needed. It is also important to note that the chipped incisors were rounded off before the impressions were made so that the esthetic appearance was maintained throughout treatment.

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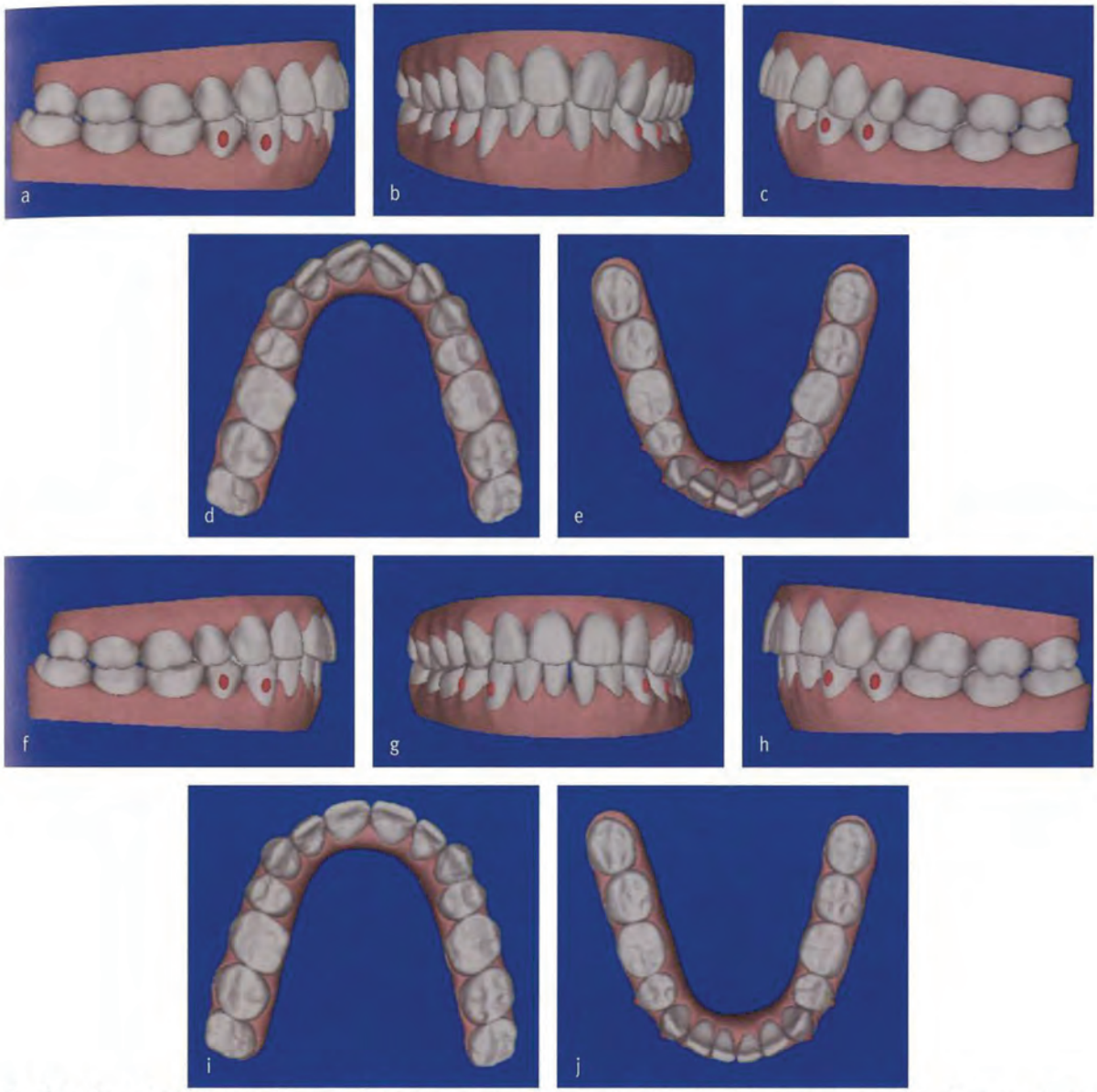


FIG 25-13 Comparison of ClinCheck images (*a to e*, preoperative; *f to j*, treatment goal) with the end-of-treatment and 3-year posttreatment images show that the goals of treatment were achievable.

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FIG 25-14 (a to k) The final result is as the ClinCheck images had predicted. Note improvement in the length of the clinical crown of the mandibular left central incisor due to the root being moved into the ridge. The maxillary midline was centered. The posterior occlusion was satisfactory, so no attempt was made to correct the mandibular midline, which was offset 1 mm to the right.

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FIG 25-15 (a to k) The 3-year posttreatment photographs show the end result to be stable.

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FIGS 25-16 TO 25-19 Patient 5.







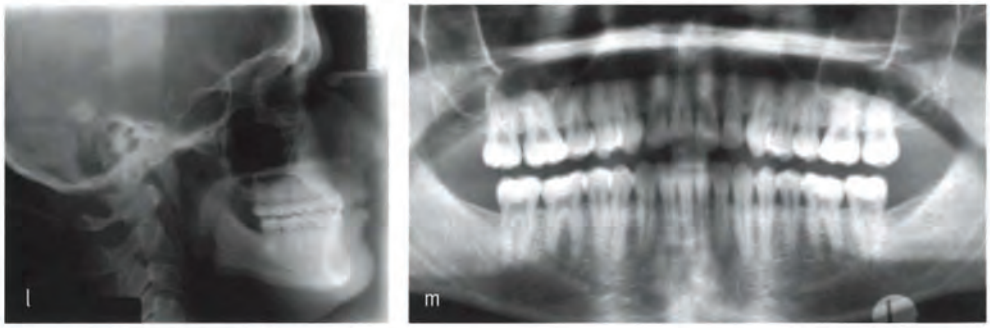




FIG 25-16 (a to n) This 25-year-old patient presented for an orthodontic evaluation complaining that his teeth had shifted since being treated with fixed appliances. Examination revealed that he had minor relapse of his occlusion, which had been corrected to a normal overbite/overjet and Class I posterior occlusion. He still wore his retainers. Further examination revealed that this patient most likely had later mandibular growth, which caused his well-aligned teeth to move into an edge-to-edge (Class III) anterior overjet relationship, with the midlines off by 1 mm. Radiographically, no concerns were noted. The patient wanted only Invisalign treatment if possible.

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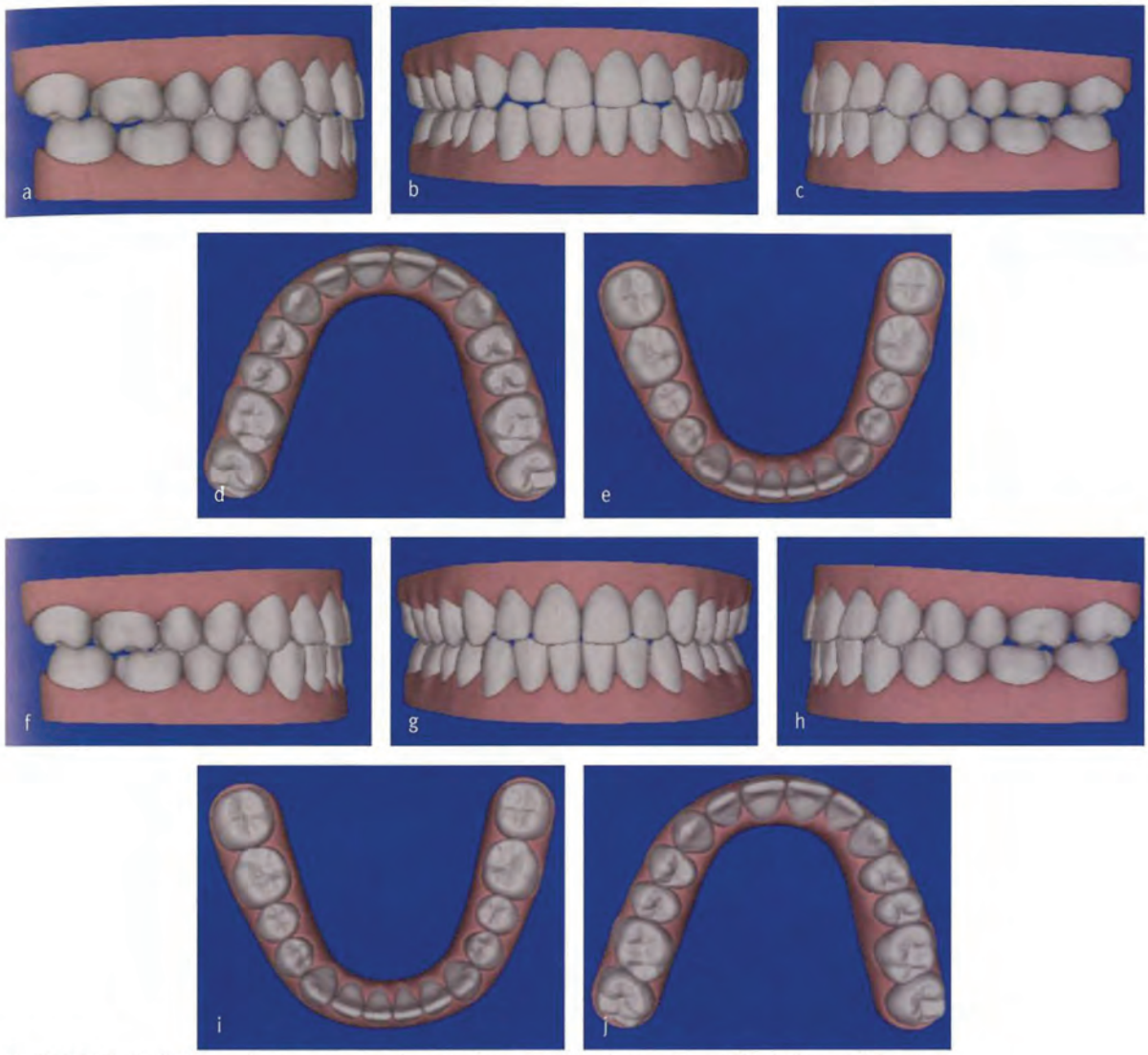


FIG 25-17 ClinCheck images (*a to e*, preoperative; *f to j*, treatment goal) correctly predicted the possible outcome.

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FIG 25-18 (a to j) Final records after 6 months of Invisalign treatment show the corrected midlines and rotations. Class III elastics had to be worn to correct the anteroposterior relationship. For this reason, clear buttons on the mandibular canines and metal buttons on the maxillary first molars were placed during treatment.



FIG 25-19 (a to c) The Class III elastics were used during the early retention stages. Retainer aligners were cut back 2 to 3 mm on the buccal to create space to place these buttons. Four-ounce elastics were used for these interarch mechanics.

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FIGS 25-20 TO 25-23 Patient 6.



FIG 25-20 (a to n) This 33-year-old patient presented with a chief complaint of "crooked front teeth." She had excellent facial esthetics with competent lips and a Class I occlusion with a unilateral posterior crossbite on the left side. There was 3-mm maxillary and 5-mm mandibular arch crowding. Overbite and overjet were normal. The maxillary midline was centered, but the mandibular midline was deviated 2 mm to the left. Radiographic analysis indicated that her skeletal pattern was well balanced.

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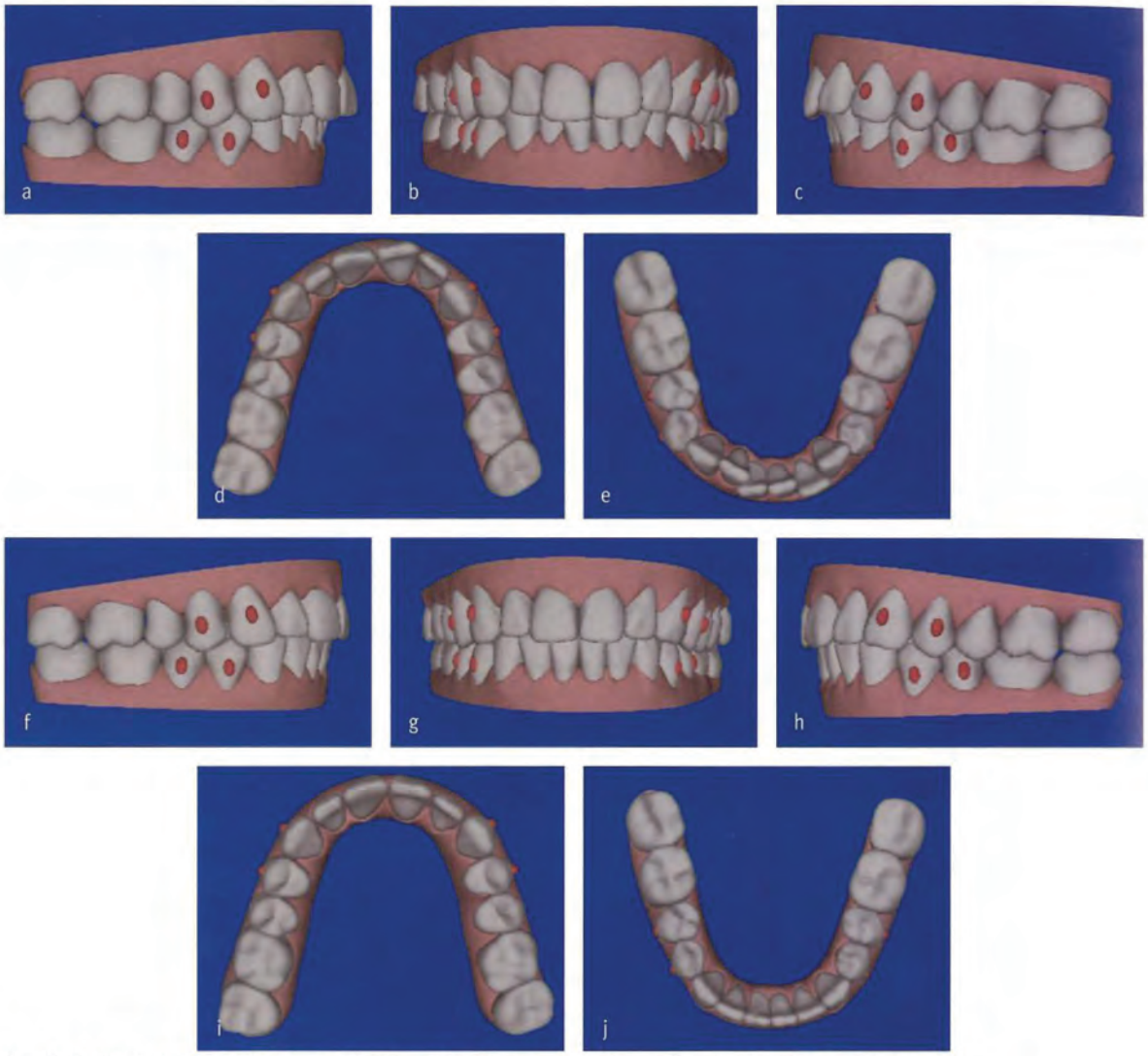


FIG 25-21 ClinCheck images (*a to e*, preoperative; *f to j*, treatment goal) correctly predicted the possible outcome.

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FIG 25-22 (a to k) Posttreatment photographs show correction of the posterior crossbite and alignment of the maxillary and mandibular anterior teeth. The maxillary crowding and posterior crossbite were corrected by expansion. Mandibular crowding was corrected by expansion and interproximal reduction.

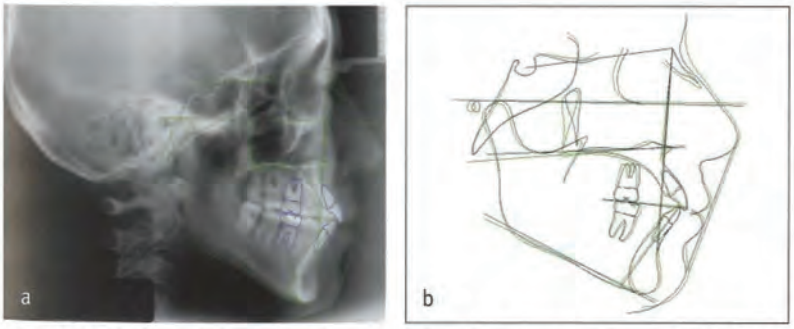


FIG 25-23 (a to c) Cephalometric radiograph and tracing reveal a well-executed Invisalign treatment for this patient. Note that the mandibular plane angle decreased 2 degrees, which reflects excellent vertical control during the posterior crossbite correction. (*c*) (tx) treatment; (S) sella; (N) nasion; (A) point A; (B) point B; (WITS) Wits analysis; (FMIA) Frankfort–mandibular incisor angle; (FMA) Frankfort–mandibular plane angle; (IMPA) incisor–mandibular plane angle; (Go) gonion; (Gn) gnathion; (U1) maxillary central incisor; (L1) mandibular central incisor; (IIA) interincisal angle; (Pog) pogonion. All measurements in degrees, unless otherwise noted.

c

Measures	Pre-tx	Post-tx	Normal
SNA	77	77	82
SNB	77	77	80
ANB	0	0	2
WITS (mm)	−3	−3	0
FMIA	58	57	65
FMA	29	28	22
IMPA	92	95	90
SN-GoGn	39	37	33
U1-SN	107	109	102
U1-NA (degrees/mm)	30/11	31/11	22/4
L1-NB	29/8	30/7	25/4
IIA	121	117	130
POG-NB (mm)	1.5	1.8	2

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FIGS 25-24 TO 25-28 Patient 7.



FIG 25-24 (a to l) This 46-year-old patient desired to have the moderate maxillary and mandibular crowding corrected specifically with Invisalign. She had previously declined a four-premolar-extraction treatment by another orthodontist. Mild protrusion was present, but the patient was satisfied with her facial appearance, and her lips were competent. She had a Class I posterior occlusion with anterior crossbite of both maxillary lateral incisors. The maxillary right canine had significant loss of clinical crown length as a result of previous periodontal disease. At initial presentation, she was in periodontal maintenance and had not lost additional bone in 4 years.

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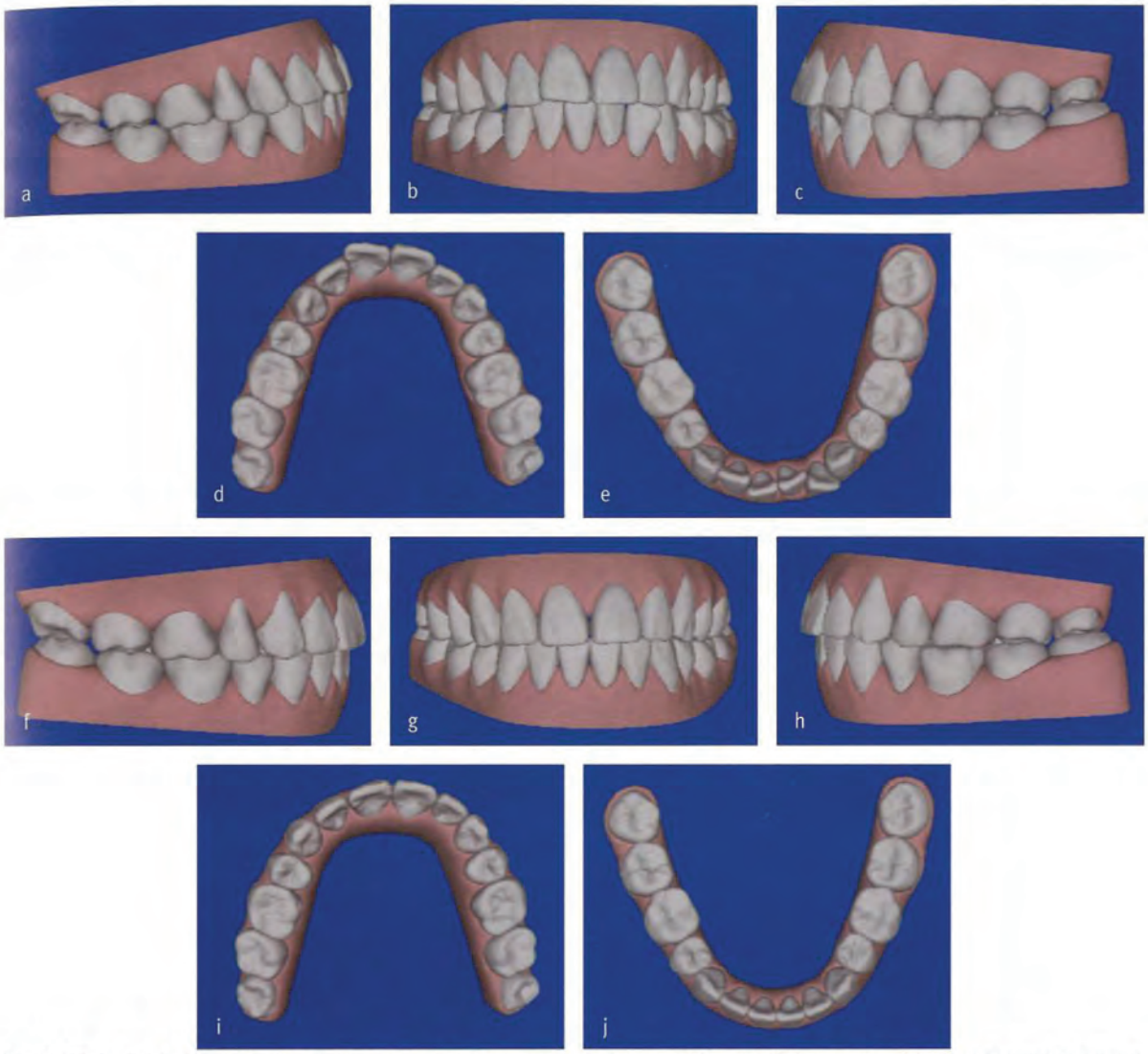
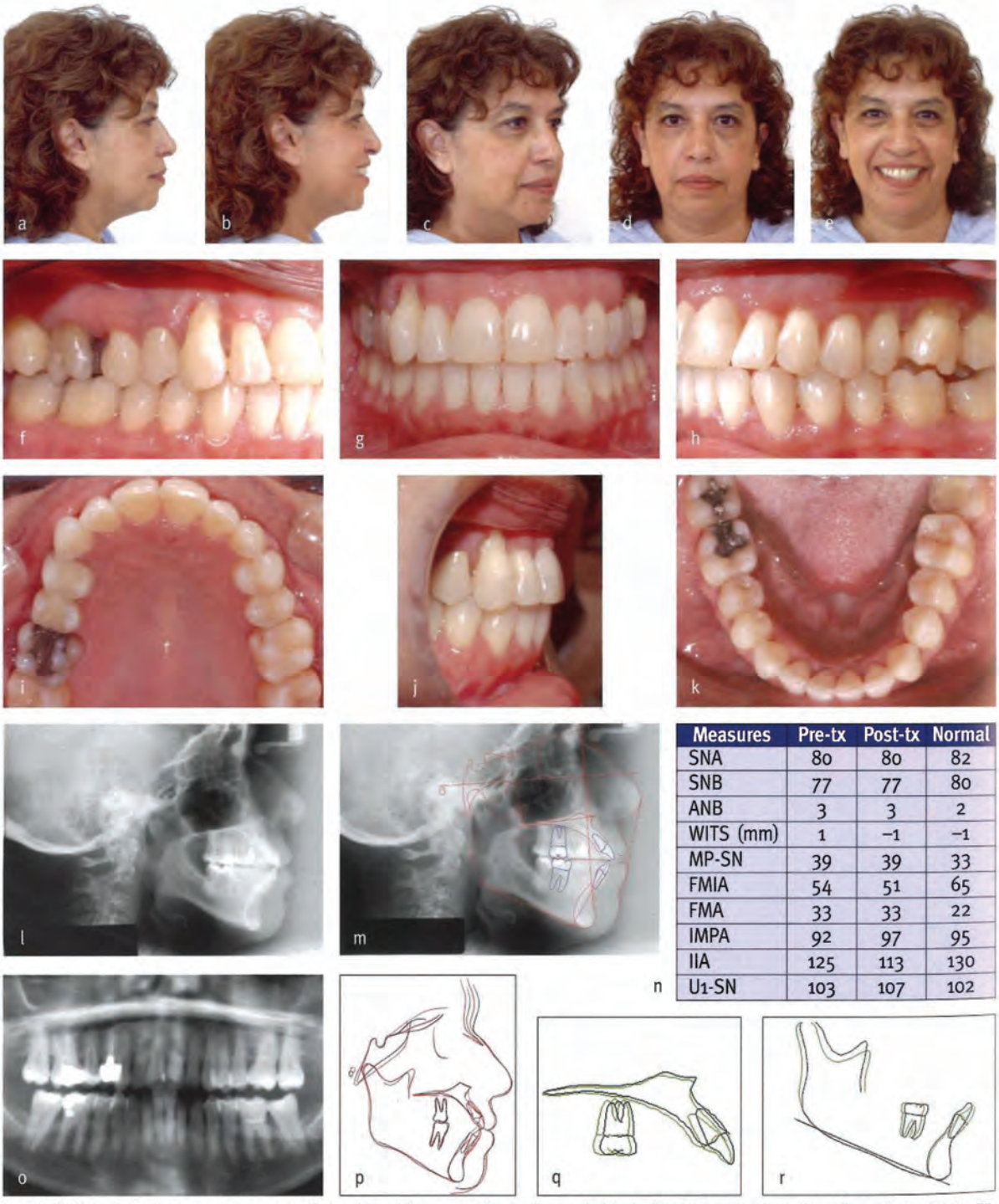


FIG 25-25 ClinCheck images (*a to e*, preoperative; *f to j*, treatment goal) suggested a possible outcome with expansion and interproximal reduction (IPR).



FIG 25-26 **(a to c)** Note the traditional use of midline elastics. Midlines were corrected by asymmetric Class II and Class III elastics attached to the teeth on clear buttons.

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Measures	Pre-tx	Post-tx	Normal
SNA	80	80	82
SNB	77	77	80
ANB	3	3	2
WITS (mm)	1	−1	−1
MP-SN	39	39	33
FMIA	54	51	65
FMA	33	33	22
IMPA	92	97	95
IIA	125	113	130
U1-SN	103	107	102

FIG 25-27 (a to r) Posttreatment images. Radiographic evidence reveals a well-executed Invisalign treatment. Correction of crowding was accomplished by creating space by IPR, posterior expansion, and distal movement of posterior teeth into the space gained by IPR. The cephalometric superimposition does not show an increase in protrusion. (*n*) (tx) treatment; (S) sella; (N) nasion; (A) point A; (B) point B; (WITS) Wits analysis; (MP) mandibular plane; (FMIA) Frankfort–mandibular incisor angle; (FMA) Frankfort–mandibular plane angle; (IMPA) incisor–mandibular plane angle; (IIA) interincisal angle; (U1) maxillary central incisor. All measurements are in degrees unless otherwise noted.

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FIG 25-28 (a to k) Postretention figures. Note the improvement in the length of the clinical crown of the maxillary right canine, which was achieved because it was retracted lingually and the root was moved lingually into the ridge. Placement of a graft further improved the crown length. The corrected occlusion was stable with diligent nighttime wear of clear retainers.

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Invisalign Patient Cooperation Acknowledgment for Orthodontic Treatment with Dr _____

Your orthodontist is dedicated to providing you the best possible Invisalign treatment. To ensure that your Invisalign treatment progresses on schedule and as smoothly as possible, it is imperative that you understand the following procedures that are involved in your treatment.

- Make sure with your general dentist that **all cleanings, fillings, or other dental work is completed prior to starting your Invisalign treatment.**
- **Please maintain your usual frequency of appointments with your general dentist** during and after Invisalign treatment.
- **Aligners must be worn at least 22 hours a day.** The only exceptions are when eating, drinking, brushing, or flossing. Please remember that Invisalign only works while you are wearing your Aligners!
- **Small tooth-colored attachments are frequently attached to your teeth.** These attachments are nearly invisible and will aid the Aligners in moving your teeth properly.
- **Whenever possible, keep teeth together** (not clenching) especially for the first 3–4 days after changing Aligners, as this speeds up the fit and efficiency of treatment.
- **Many patients want to bleach their teeth** during treatment using their Aligners. Ask us about this benefit, as it is included in the cost of your Invisalign treatment.
- **It is critical that you follow the instructions covered in the use and care pamphlet in the Patient Starter Kit** regarding inserting and removing the Aligners, cleaning the Aligners, and proper brushing and flossing.
- **Always store your Aligners in their case** when they are not being worn to avoid loss. If you lose an Aligner, it will cost you $75.00 per Aligner to replace.
- **It is your responsibility to make sure you do not go to the next Aligner unless the Aligner fits completely with no space between the teeth and Aligner.** If you notice that the Aligner has space when due for a change in Aligners, you should keep that Aligner until it fits with no space.
- Because the Aligners are designed to sequentially move your teeth, it is very important to **wear each Aligner in the order prescribed by your orthodontist.** Usually you will wear each Aligner for about two weeks, but sometimes a few days to a week longer is required if wear is less than 22 hrs/day. Do not wear Aligners out of order.
- **Always keep at least the last 3 Aligners** in case of loss of a presently used Aligner or in case an Aligner does not fit. Your orthodontist may go back in sequence to catch up to have Aligners correctly fit.
- **Modifications to your Aligners or several additional Aligners or occasionally regular (clear) braces may be needed at the end of your treatment** in order to completely finish your treatment.
- After your treatment is complete, **clear** retainers are designed to maintain the smile you've invested in. Usually you will wear these for **6 months full time and then indefinitely at night while sleeping.**
- **Keep your scheduled appointments**—this is the only way we can be sure that your treatment is progressing as planned.
- I consent to the making of orthodontic records, including x-rays, photographs, prescriptions, and other information which may include personal identification, before, during, and after treatment, and to the orthodontic treatment prescribed by my doctor. I also consent to my doctor and/or Align Technology forwarding any of my orthodontic records to other licensed dentists and organizations employing licensed dentists for the purpose of consulting regarding my treatment.
- Finally, I consent to the use of my orthodontic records (eg, dental x-rays, photographs, and plaster models) for purposes of orthodontic consultations, educational and research purposes, publication in professional journals, or use in professional collateral materials, but not to use or disclosure of my specific name, address, or other personal identification information.
- Please don't hesitate to call our office if you should have any questions or problems with your Aligners.

I have read and understand these tips to my successful Invisalign treatment.

Patient Signature _____ Date _____
Parent/Guardian Signature _____ Date _____

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FIG 25-29 *(left)* Informed consent form.

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chapter 26

INTERPROXIMAL ENAMEL REDUCTION

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Most patients seek orthodontic treatment because of crowding. According to a 2003 study by Meier et al,[1] 87% of randomly interviewed individuals interested in orthodontic treatment with the Invisalign System displayed various severities of crowding. Crowding problems may be eliminated by creating sufficient space. The traditional means to accomplish this are extraction of posterior teeth (mostly premolars) or incisors (mainly in the mandible), expansion (mainly in the sagittal plane, and to a limited degree also in the transverse plane), and interproximal enamel reduction (IPR). The appropriateness of these procedures for a given malocclusion depends on many factors.

IPR has several notable advantages, especially when patients are treated with the Invisalign System. In the course of treatment, it might become obvious that teeth collide, though this should have been noticed already in the ClinCheck images. At such times, IPR might be the most reasonable approach.

It is commonly accepted that IPR removes a certain amount of enamel from the proximal tooth surface. In orthodontic parlance, this is referred to as *stripping*. Alternatively, terms such as *slicing*, *slenderizing*, *trimming*, *mesiodistal (enamel) reduction*, *re(ap)proximation*, or *interproximal wear*, *selective grinding*, *reshaping*, *recontouring, coronoplasty*, and *Hollywood trim* are sometimes used.[2–4] The term *stripping* is ambiguous and should not be used. Other terms listed above downplay the seriousness of this procedure and thus are also inappropriate. *Interproximal enamel reduction* is the most neutral and accurate term and will be used in this chapter.

History of Interproximal Enamel Reduction

The first orthodontist to advocate IPR as a means to resolve asymmetry of tooth size was Ballard in 1944.[5] Later, Bolton concluded that this procedure was best to correct tooth-size discrepancies between the maxillary and mandibular dental arches.[6,7] In 1954, considerable attention was drawn to IPR by Begg, whose article on Stone Age man's dentition demonstrated that attrition can occur to a remarkable degree.[8] According to Begg, tooth wear helps to prevent impaction and crowding of third molars. The first clinician to describe how to perform IPR was Hudson in 1956.[9] According to Hudson—and others later—IPR is completed by polishing the teeth and applying topical fluoride.[2] This suggests that IPR is not simply a procedure of grinding off enamel, but also that it has to be performed with the same care as any other invasive procedure. Hudson was also the first to give exact numbers about enamel thickness and the amount of safe IPR. Subsequently, other researchers reevaluated the question of enamel thickness.[10]

The first study on IPR was conducted by Rogers and Wagner, who investigated the effect of fluoridation after enamel reduction in vitro.[11] They showed that fluoride significantly lowered the rate of decalcification. This study provided the first scientific argument against critics who opposed IPR on the basis that irreplaceable material was removed and tooth damage inflicted. Opponents had argued that enamel injury induced through IPR could lead to caries and ultimately to loss of the entire tooth.

A new era in IPR began in 1985 when Sheridan first presented his concept of air-rotor stripping.[12] Sheridan was obviously heavily influenced by Begg. IPR, which had been mainly restricted to anterior teeth, was extended by Sheridan to include posterior tooth segments. According to Sheridan, this allowed for the removal of up to 8 mm of tooth material. Also, Sheridan realized that effective and sufficient IPR in the posterior segments of the dental arch could not be accomplished easily and safely with rotating disks. To overcome this problem, Sheridan propagated tungsten carbide burs at high speed.[12] He named his IPR method *air-rotor stripping* (ARS).[12,13]

Another person who had a strong impact on IPR was Zachrisson.[4] Although others had already mentioned the influence of IPR on the gingiva ("gingival improvement"),[14] Zachrisson was probably the first to emphasize the importance of enamel reduction to avoid unesthetic void interproximal spaces ("black triangles").

A new concept of IPR, in which mechanical enamel removal was combined with the application of a microabrasive chemical (37% phosphoric acid), was advocated in studies conducted by Joseph et al[14] and Rossouw and Tortorella.[15] These studies showed that this combination IPR method produces relatively smooth surfaces, which have a potential to "heal themselves" by crystal growth. These reports of in vitro studies had no clinical impact: nothing of substance was subsequently published about this combination IPR. In contrast, Piacentini and Sfondrini considered enamel surfaces treated by this approach "susceptible to decalcification," as the clinician is unable to check whether the patients use calcifying or fluoridating solutions.[3] Subsequent to these milestone articles, much has been published on IPR.[16–27]

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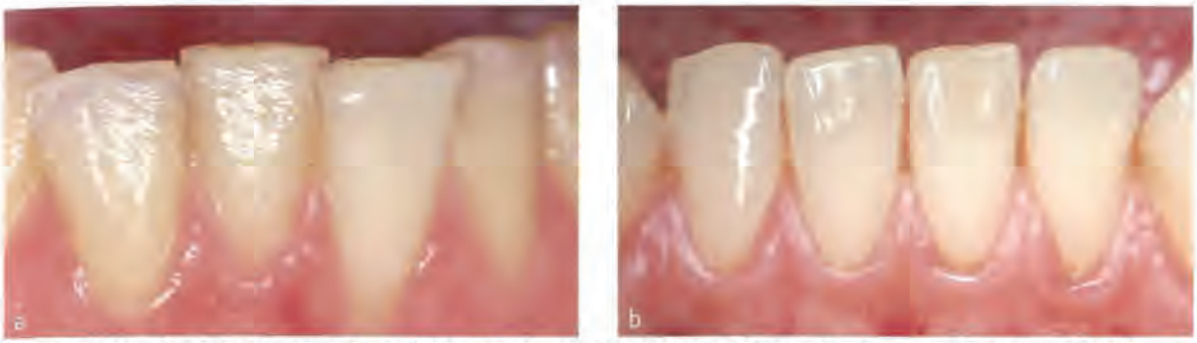


FIG 26-1 Teeth with a triangular crown shape (*a*) are better suited for IPR than are those with a square crown configuration (*b*).

Indications

The following indications for IPR are listed in the order of their presumed importance:

- Elimination of anterior and posterior crowding.
- Avoidance of open gingival embrasures.[4,28–30] This is of particular concern for patients with advanced periodontal disease and gingival recession.
- Correction of tooth-size discrepancies between the two dental arches. This problem could also be solved by widening the relatively smaller teeth through bonding or veneers, but IPR is more readily available and far less expensive.
- Establishment of congruent tooth morphology on both sides of the dental arch.
- Improvement of occlusion (ie, correction of improper interdigitation, overjet, and overbite). This procedure can sometimes help to correct a sagittal skeletal malocclusion by limiting the corrective movements to the dentoalveolar complex.
- Reduction of one-jaw or bimaxillary protrusions without extractions.
- Recontouring of abnormally shaped teeth toward a more ideal morphology.[4]
- Prevention of crowding.[31,32] This effect remains unsubstantiated.[33]

Contraindications

Contraindications are more difficult to list because they are seldom clearly stated. Some important considerations are as follows:

- IPR is not an option in patients with microdontia or an abnormal crown shape (ie, their widest extension is in the gingival, not the occlusal, area). The possible impact of IPR in teeth with abnormal crowns is not only poor esthetics, but also food impaction that can lead to further complications.
- Teeth with a square crown configuration—as opposed to teeth with a triangular crown shape (Fig 26-1)—are poor candidates for IPR.
- Hypersensitivity to hot or cold may be a reason to avoid IPR, as the hypersensitivity might increase after IPR.
- It has been argued that closeness of roots is a reason to avoid IPR.[34] Although not proven, the presumption prevails that the more the roots of adjacent teeth approach each other, the narrower the bone between the roots becomes, which in turn reduces the blood supply and ultimately makes the periodontium less resistant to bacterial invasion. This argument seems unreasonable because in many crowding situations the roots are closer to each other before alignment than they are after—even when IPR was performed.[35] Furthermore, a study by Årtun et al showed that root approximation caused by orthodontic treatment did not increase a patient's risk of developing periodontal problems.[36] Similarly, Crain and Sheridan did not see differences in the alveolar crest morphology when they compared areas with and without IPR.[37]
- Although poor oral hygiene is sometimes mentioned as a contraindication, this argument has no merit because (*1*) orthodontic treatment of any kind should not be undertaken in any patient with compromised oral hygiene; (*2*) if IPR is performed to resolve crowding, the accessibility to all interproximal tooth surfaces is improved after treatment, which makes interproximal hygiene (ie, salivary flushing or flossing) easier; and (*3*) not only is plaque removal easier after IPR, but even the retention of plaque may decrease if the correct polishing technique is used after IPR.

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