Auxiliary springs in continuous arch treatment:
Part 1. An analytical study employing the finite-element method

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This report describes the results of a finite-element analysis with ANSYS (Version 4.3) from Swanson Analysis Systems and 1 mm-long, 2-D elastic beam elements to modify and refine the designs of maxillary and mandibular springs for space-closure management. This system permitted static analysis by means of modern software systems instead of expensive and cumbersome mechanical bench studies. Our examination of anterior and posterior reactions led to what we believe are optimal designs with clinically manageable moment/force ratios and new canine brackets that accommodate these springs within the framework of conventional and straight-wire appliance systems.

Three degrees of freedom were used at each node for translations in the x and y directions and a rotation about the z axis, producing 182 elements with 183 nodes for the mandibular model and 146 elements with 147 nodes for the maxillary model. Elgiloy retraction spring models (0.1650 inch x 0.02150 inch) in the edgewise mode were developed so that the effects of three different preactivation bends could be refined by computer analysis. Sixty-four analyses were performed for each spring, with each of three angle bends (θ₁, θ₂, and θ₃) varied from 0° to 45° in 15° increments. The employment of this computer method promises to simplify the design and development of complex interacting orthodontic systems. Clinical cases are presented in Part 2 of this series, which illustrates the application of auxiliary springs.

While the development of Begg brackets has continued to evolve in the direction of greater degrees of freedom, edgewise modifications have been evolving toward a form that entails precise movement during extraction mechanics.¹ A chief goal in designing edgewise brackets has been to achieve tooth translation in cases where reciprocal movement, anterior retraction, or posterior protrusion is desired. However, this result has been difficult to achieve because application of a simple force may cause translation, rotation, or a combination of the two on a tooth. If a line of force is placed close to the tooth’s center of resistance, the effect will be one of translation rather than rotation or tipping² (Fig. 1, A).

The center of resistance for a single-rooted tooth is located approximately 40% of the way from the alveolar crest to the apex, and 1 to 2 mm below the furcation of multirooted teeth. This point should be analogous to the center of the root (centroid) between the apex and alveolar crest.³ Unfortunately, the forces generally placed on the bracket during space closure are not in line with the centroid but often are nearly perpendicular to the bracket-
Fig. 1. A, A force (F) acting through the center of resistance (CR) produces translation without rotation. The center of rotation is at infinity. B, A force (F) acting at any point other than the center of resistance produces a moment resulting in tipping (MF). In this and in the following figures, MF is understood to be the resultant moment of the applied force and not an applied moment. C, The addition of a moment (Mc) from a couple is required to counter the moment of the force (MF) to effectively produce translation. The center of rotation is at infinity. The moments MF and MC are in opposite directions at 3000 gm-mm each. The moment of the couple (Mc) = 3000 gm-mm and the force = 300 gm. This gives a 10/1 M/F ratio.

It is important to realize that the center of resistance varies with the absolute root length and the degree of periodontal support, which is affected in turn by alveolar bone height. The amount of tipping depends not only on the forces used, but also on the anatomy of the tooth and its environment. This is precisely why it is so difficult to translate teeth and close spaces in adult patients with a history of generalized bone loss. As the distance from the bracket to the center of resistance increases, a larger moment and more tipping will occur, causing progressive binding of the arch wire in the bracket as it tips.

In this type of situation, a new student of orthodontics may make the mistake of increasing the force at the bracket, thinking it insufficient. Since M = D × F, the moment of the force increases, tipping worsens, and tooth movement may cease altogether. Light arch wires may also be overpowered and start to deflect. To translate a tooth, the practitioner needs to combine the force at the bracket with a large moment from a couple to counteract that generated by the force used in space closure. This couple is simply a configuration of forces that may produce a moment or turning tendency but are not relative to any point. The use of such a technique will avoid the tipping and move the center of rotation to infinity. The idea is to apply an effective "counter-moment," juggling the moment/force ratio (M/F) to ensure controlled bodily movement. It should be remembered that the moment/force ratio is directly related to the millimeter distance from the point of force application to the location of the equivalent force. A M/F ratio of 10:1 is generally considered optimum for translation in healthy teeth, but it may need to be higher in periodontally compromised situations. Fig. 1, C illustrates that the moment of a couple must balance the tipping moment produced by the force for space closure at the bracket and therefore must move in an opposite direction. For
the sake of simplicity, the M/F ratios at the bracket and at the center of resistance are considered equivalent in descriptions of the reaction of the teeth to a force system.

Fig. 2, A, illustrates a more traditional means of gaining controlled tooth movement. Simple gable bends in the arch wire, in combination with a force from an elastic or simple spring, are used to produce a couple intended to overcome tipping during space closure. This traditional technique is workable but often cumbersome, since it is nearly impossible for the clinician to know whether he has "balanced" the gable bend (magnitude of the couple) with the force applied at the bracket or tube. The induced moment of the uprighting bend of the wire is almost always in a direction opposite the moment of the force of the elastic at the bracket. Too much of a gable may actually open an extraction space, while excessive elastic force and an insufficient gable can tip the teeth into the space. A centered gable bend will produce equal and opposite moments of the roots, but an off-center bend will produce unequal moments; which become further unbalanced when a gable bend is moved progressively away from the middle of the extraction site during space closure. If equal moments are desired, the wire must be re-removed and new gables put in place after significant tooth movement.

Fig. 2, A, Forces and moments produced by a center-gabled arch wire closure system. B, Forces and moments produced by an activated Bull loop system.

Finishing an occlusion with teeth "dumped" and nonparallel roots adjacent to extraction sites may put the patient at risk of such posttreatment ills as (a) opening of extraction sites, (b) poor interproximal contacts with periodontal sequelae, (c) deep bites with attrition, and possible TMJ problems. The use of a simple "Strang-type" or modified Bull loop, as seen in Fig. 2, B, can be effective in generating an ideal moment/force ratio for translation. Unfortunately, its range of activation is so limited that it is not generally practical. An ordinary loop with a helix has an improved range, but it cannot generate an ideal M/F ratio and may allow tipping during space closure. If a clock loop is needed to engage multiple second-order bends or gables to allow for arch engagement, it is likely that controlled movements have already been lost.

Traditional Begg treatment philosophy relies on tipping and light force to move teeth rapidly during early stages of treatment and on large moments with uprighting auxiliaries to achieve movement during the finishing stage. A great deal of effort may be required to upright an intentionally tipped tooth, especially in patients with a strong musculature.

Bracket modifications

A more recent and radical departure from traditional wire bending to achieve translation is modification of the bracket, as achieved by Andrews in his straight-wire appliance. In this instance the couple or root rotation is produced by deflecting a straight archwire into a tip manufactured directly into the bracket. A balance is achieved by applying a horizontal force. Andrews' "space-unit" analysis is a unique attempt to calculate the specific
amount of moment required, based on the size of the extraction space to be closed. For example, a specific canine bracket could be chosen with up to four additional degrees of tip incorporated to gain translation during space closure of more than 5 mm.\(^\text{10}\)

Although this technique can work well in many cases, it is nearly impossible to calculate the exact degree of force with its own inherent moment needed to counter the built-in moment of the bracket. Vertical forces may also show up because of unbalanced moments. A price may be paid for the privilege of less wire bending, since this desirable attribute may also create unwanted side effects seen during tooth movement.\(^\text{11}\)

It is usually expedient to start fixed appliance treatment with very light wires. If no initial retraction forces are placed at the bracket, the moment of the couple caused by the built-in tip is expressed. The lack of "counterpoise" in the force used to close the space, along with the moment of this force, can prove troublesome because teeth will tip in the same way as if excessive second-order bends or gables were being placed. Brackets with a large degree of tip may initially induce tooth movement in a direction opposite that desired. Protrusive dentitions and already compromised periodontium may be aggravated by resultant flaring. The initial wire "round-tripping" effect can, of course, be avoided with tie-backs and appropriate anchorage during treatment planning and execution.
Current segmented-arch techniques offer systems that produce controlled tooth movement and excellent moment-to-force ratios, but they contain numerous components that may be difficult to manipulate. The lack of a continuous main arch between anterior and posterior segments may allow for an overall reduction in force as the sliding resistance of a main arch is eliminated. This system, however, cannot prevent anterior and posterior segments from leaving the plane of occlusion as a result of errors in the M/F ratio between segments because the segmented-arch technique lacks the "fail-safe" mechanism of the main arch approach.

Ideally, a "user-friendly" system should use simple sliding mechanics to manage translatory space closure on a straight-wire system without causing "round-tripping" or taxing anchorage. This should be accomplished without deepening the bite or tipping teeth into extraction spaces. Such a system should also manipulate anterior and posterior segments with differentially controlled anchorage and tooth movements, as do the advanced segmental techniques pioneered and developed by Burstone and modified by Braun. At present, no specific appliance system has gained universal acceptance.

MATERIALS

The Appliance

An auxiliary spring technique that uses segmental principles has been devised for use with conventional straight-wire or traditional edgewise mechanisms. Unlike the conventional segmental systems, this auxiliary technique accomplishes space closure with sliding mechanics on a continuous main arch wire. The system consists of specially designed 0.017-inch 0.022-inch heat-treated Elgiloy springs (Rocky Mountain Orthodontics, Denver, Colo.) that are inserted into buccal and gingival tubes, which are part of the molar and canine brackets (Fig. 3, A). Only the special canine brackets need to be substituted in existing edgewise prescriptions in cases where the first molar brackets include gingival auxiliary tubes. Other than the canine modification, the 0.018-inch edgewise Bio-progressive or Roth-type appliance (Rocky Mountain Orthodontics, Denver, Colo.) is used in this report. The canine brackets have been designed to facilitate insertion or removal of the springs without the necessity of retying existing ligatures. There are 0° torque and 6° tip in the mandibular canine bracket; 0° torque and 10° tip in the maxillary canine bracket.

Notice in Fig. 3, B that the mandibular spring appears similar to traditional retraction springs except for the extra helix in the anterior (α) portion. This helix, in conjunction with the gables placed in the posterior (β) legs of the spring, provides the required couple "counter-moment" for the moment of the force and allows for the translation of the canine or molar during space closure. The main spring helices are placed in the area of the extraction site. The maxillary spring is also shown (Fig. 3, C).

There are three angles in the spring to consider: θ₁ and θ₂ comprise the bends posterior and anterior to the main contraction helices, while θ₃ is the angle of the anterior leg of the helix.

The moments imparted by the helix and the gables of the spring must be balanced, or a couple will appear in the mechanism, causing unwanted or uncontrolled vertical forces. Such unbalanced vertical forces are commonly seen in base arches, or utility arches in the form of supereruption of the molars. In these cases a large extrusive force will be produced if vertical anchorage is not first obtained with segmental arches or auxiliaries. The large moment is a result of the long distance from the incisors to the molars.²

The preadjusted springs are first placed into the mesial of the auxiliary molar tube and then inserted into the mesial of the canine tube. The excess wire at the distal side of the auxiliary molar tube is activated 2 mm by pulling and cinching the wire at the end of the spring. All the spaces may be closed in one operation or by separate canine retraction methods, depending upon the requirement of the clinician.

The main arch-wire configuration and the proper forces and moments (moment/force ratio) are expressed by predetermined auxiliary spring activations for the most common treatment situations. These include (a) reciprocal space closure, (b) maximum posterior anchorage with maximum anterior retraction, (c) maximum anterior anchorage with posterior protraction, and (d) gross shifting of the midline.

COMPUTER-AIDED ANALYSIS OF SPRING AUXILIARIES

Finite element model

It has been mentioned that it is difficult to juggle M/F ratios in spring design so as to obtain translatory movements. In effect, it is a problem of statics to be solved with advanced engineering
techniques. Finite element models of mandibular and maxillary versions of the spring were developed so that the effects of different preactivation bends could be refined by computer analysis. Nonlinear analyses were then performed for 0 to 4 mm activations. This amounted to 64 analyses for each spring, since all three angle bends ($\theta_1$, $\theta_2$, and $\theta_3$) were varied from 0° to 45° in 15° increments. The examination of anterior and posterior reactions led to probable optimum designs for anterior retraction, reciprocal attraction, and posterior protraction.

The analysis of orthodontic springs can be performed by either analytical or experimental techniques. Since 128 different configurations were to be studied, an analytical method was preferable. Certain inherent difficulties exist in developing a "closed-form" solution. These include (1) a complex geometry arising from the helices, (2) the statistically indeterminate nature of restraints, and (3) the nonlineairties resulting from the large deflections involved. These complexities can be handled in analysis by the finite-element method.16–21

### Geometry

The finite-element models were created with the help of ANSYS (version 4.3), a general-purpose finite element package from Swanson Analysis Systems. Computations were performed on a Vax-750 computer. Each spring was modeled with 2-D elastic beam elements. This element has three degrees of freedom at each node: it allows translations in the x and y directions and a rotation about the z axis. For the straight portions of the spring, the elements were approximately 1 mm in length; for the helices, there was an element for every 15° arc. In all, there were 182 elements with 183 nodes for the mandibular model, and 146 elements with 147 nodes for the maxillary model.

### Table I. Results of activation for three conditions of the mandibular spring with preactivation angled bends $\theta_1$, $\theta_2$, and $\theta_3$

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<th>Condition</th>
<th>Activation (mm)</th>
<th>Horizontal force (gm)</th>
<th>Vertical force (gm)</th>
<th>$\alpha$-moment (gm-mm)</th>
<th>$\beta$-moment (gm-mm)</th>
<th>Spring rate (gm-mm)</th>
<th>$\alpha$-M/F (mm)</th>
<th>$\beta$-M/F (mm)</th>
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<td>C. Maximum posterior protraction ($\theta_1 = 45^\circ$; $\theta_2 = 30^\circ$)</td>
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*Closing force.
†Extrusive force.
‡Counterbalance.

Cross-sectional properties
Both springs had rectangular cross sections of 0.419 × 0.546 mm (0.1650 × 0.02150 inch) in the edgewise mode. The smaller dimension was the height, and the larger the width. Their cross-sectional area was 0.229 mm² and the area moment of inertia was 0.00335 mm⁴. A shear-deflection constant of 1.20 for rectangular sections was also used.

Material properties
The springs were made of Elgiloy (Rocky Mountain Orthodontics, Denver, Colo.), so a Young's modulus of 2.00 E7 gm/mm² and a Poisson's ratio of 0.300 were used.

Analysis
The deflections produced by orthodontic springs require a large deflection analysis based on updated tangent stiffness matrices. The Newton Raphson method was used to determine the nonlinear solution arising from the large deflections. Stress stiffening (enhanced stiffening caused by the stressed state) was also taken into account. All analyses were performed in two load steps. The first consisted of bringing the anterior and posterior ends into proper position (the equivalent of placing the springs in the brackets without activation) by specifying all translations and rotations at both ends except for the posterior horizontal displacement. At the end of this load step, anterior (α) and posterior (β) moments were present at the two ends, with no
RESULTS

We examined 64 different configurations for both of the mandibular and maxillary models—the equivalent of varying the three bends from 0° to 45° in 15° increments. The differential manipulation of the M/F ratios influences the degree of tipping versus body movement and therefore affects anchorage considerations.
Fig. 6. A, Moment/force ratios versus activations for reciprocal closure. B, Moment/force ratios versus activations for reciprocal closure. Table I, A-C. Results of activation for three conditions of the mandibular springs for the preactivation angled bends, $\theta_1$, $\theta_2$, and $\theta_3$.

**Mandibular model**

$\theta_1$ $\theta_2$ $\theta_3$

45° 45° 0° → Anterior retraction
45° 45° 15° → Reciprocal attraction
45° 45° 30° → Posterior protraction

An examination of the "reciprocal attraction" condition in Table I, section B, shows nearly 450 gm of horizontal force with approximately a 2200 gm-mm moment for both posterior and anterior spring sections. At 2 mm of activation, the M/F ratios begin almost at 5 and go to a value of approximately 9 at 1 mm of remaining activation. When the spring's horizontal activation is finally expended, it continues to operate as a root spring, increasing the M/F ratios to 16 and above. Bend $\theta_3$ is at 15°. Bends $\theta_1$ and $\theta_2$ have been kept at 45° for this and all other applications.

Examination of maxillary spring anterior and posterior reactions led to the selection of the following model. Note that as the configurations of the spring are modified to conform with the maxillary buccal fold, the $\theta_3$ activations are slightly different.
Maxillary model
\[
\begin{align*}
\theta_1 &\quad \theta_2 &\quad \theta_3 \\
45^\circ &\quad 45^\circ &\quad 15^\circ \rightarrow \text{Anterior retraction} \\
45^\circ &\quad 45^\circ &\quad 30^\circ \rightarrow \text{Reciprocal attraction} \\
45^\circ &\quad 45^\circ &\quad 45^\circ \rightarrow \text{Posterior protraction}
\end{align*}
\]

Computer-generated Figs. 4, A and 5, A detail the boundary conditions and linear dimensions of the mandibular and maxillary springs, respectively. They illustrate the actual preactivated appearance of the auxiliaries in a passive state, before placement in the canine and molar tubes. Figs. 4, B and 5, B represent the springs placed in the arch before activation. The computer program shows the deflected appearance of the spring as a result of its preactivated bends at \(\theta_1\), \(\theta_2\), and \(\theta_3\). Figs. 4, C and 5, C show a typical 2 mm clinical activation. The figures shown are clinically accurate visual simulations of the load steps involved in the analysis.

Graphs (Figs. 6, A and B) show how closely the anterior and posterior M/F ratios are balanced during deactivation in the mandibular and maxillary springs, respectively. The frequently used reciprocal attraction conditions are portrayed.

**DISCUSSION**

The level of the M/F ratio regulates the type of tooth movement. "Controlled tipping" occurs at an M/F ratio nearing 7, translation appears at 10, and root uprighting is seen at M/F ratios over 12. The translation desired in space closure is derived from a progression of tipping, translation, and root uprighting during a single activation.\(^2\) It is therefore necessary to allow for full expression of the uprighting moments before reactivating the spring. A 6-week period may be required to allow for full uprighting.

Differential manipulation of the M/F ratios can influence anchorage considerations. Comprehensive posterior anchorage control is accomplished with standard adjuncts such as lingual arches, transpalatal arches, Nance arches, headgear, and elastics, as traditionally used in edgewise therapy. In situations where posterior protraction is needed, as with Class II molars, it is important that the posterior segment move forward more than the anterior segment is retracted. As long as the posterior segment has an M/F ratio in the neighborhood of 7, while the anterior dentition ratio is closer to 12 during spring deactivation, intraarch differential anchorage is achieved. If maximum mandibular anterior retraction is desired, as in a severely protrusive dentition with lip strain, \(\theta_3\) should be 0°. It is likewise important that posterior anchorage be maintained while the anterior teeth are tipped lingually under control. In this latter situation, a lower initial M/F ratio in the anterior segment and a higher posterior M/F ratio are advantageous.

It is important to realize that when one deliberately "unbalances the moment" to create intraarch anchorage, vertical forces appear in the same way as described with base or utility arches. When the posterior M/F ratio is greater than the anterior, there is a slight extrusive vertical force in the posterior, and an intrusive force in the anterior. The opposite holds true for the posterior protraction situation. Because it is almost impossible to balance any system completely, vertical forces may also appear in reciprocal closure. As spaces close, the main activation loops change their relationship to the center of the extraction site. These forces are considered minimal, however, and are dissipated through the main arch wire to contiguous teeth by the forces of occlusion.

**SUMMARY AND CONCLUSION**

Until this analysis, we had generalized the degree of the anterior and posterior bends because "optimum" angles had never been calculated for these specific auxiliaries. Previous clinical experience that used these and similar auxiliaries helped us preselect these particular configurations from the potentially infinite number of shapes, dimensions, and materials that could be analyzed. The springs used in this report had been found to be particularly effective in clinical practice for space closure and as root springs. Little difference was apparent between the angles that were used clinically in the case examples and the optimal values selected after sophisticated computer modeling. This analysis was essential to demonstrate that forces and moments are capable of being manipulated to generate clinically acceptable tooth movements with a spring configuration of this type and material. Theoretically, there is an infinite number of variations of spring angles, diameters of helices, compositions, and degrees of activation that will produce the same values.

Because translation actually includes a progression of tipping-translation-uprighting, some degree of interaction with the main arch, however minimal, must occur during movement. This situation is encountered in all types of sliding mechanics.
More sophisticated programs are being developed to analyze the interaction of various appliance systems, including the main arch and various auxiliaries such as headgear, base arches, and lingual and palatal arches.

The use of advanced computer-aided design engineering by the finite-element method has been applied to the refinement of existing stainless steel alloy auxiliary-spring design and activations. The use of available analytical techniques, as described in this study, reflects an advance in the technology of design and development of orthodontic appliance systems. The ability to create visual representations of complex configurations before placement and after placement with deformation, and to envision activations while obtaining data on forces, moments, and rates adds a new dimension and ease to clinical research in biomechanics.

Three clinical cases illustrating reciprocal closure, posterior protraction, and anterior retraction will follow in the next article in this two-part series.

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REFERENCES
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