Finite element-based cephalometric analysis

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The purpose of this paper is to apply a known, but difficult-to-understand, analytical tool to a common clinical setting in orthodontics. There are many different morphometric methods available for the evaluation of cephalometric data. The main objective of the computer program developed for this goal is transformation of one of these methods into one that is both interesting and usable for the clinical orthodontist. Finite elements were chosen for this analysis of serial, lateral cephalometric radiographs.

The finite element method has proven to be a useful tool in a number of biological applications. The mathematical limitations inherent in linear methods from plane geometry were described accurately many years ago by Moyers and Bookstein,[1] specifically as they relate to cephalometrics. Finite element analysis, the biorthogonal grids of Bookstein,[2] and related techniques generate a mathematical matrix of transformation related to both size and shape. The use of transformations in this manner establishes a greater degree of sophistication in the analysis of craniofacial growth and development.

To illustrate the effects of treatment or growth with serial headfilms, linear and angular cephalometric measurements rely on traditional lines of comparison chosen by the originator of the particular analysis. The Steiner[3] and Ricketts[4] superimpositions are but two examples of the many ways in which films can be superimposed. This visual comparison is normally supplemented with a comparison of linear and angular measurements from the two films. Since there are many static cephalometric analyses available, as

Abstract

The finite element method has proven to be a useful tool for morphometric analysis in craniofacial biology. However, few attempts have been made to adapt this method for routine use by clinicians. The CEFEA program incorporates the advanced features of the finite element method but bypasses the detailed understanding of the engineering and mathematics previously required to interpret results. The program uses the color graphics display of common personal computers to show size change, shape change, and angle of maximum change. These are pictured as colored triangles of clinically relevant regions between pre- and mid- or posttreatment lateral headfilms. The program is designed to have features of interest in both clinical practice and research.

Key Words

Finite elements • Morphometrics • Cephalometry • Computers

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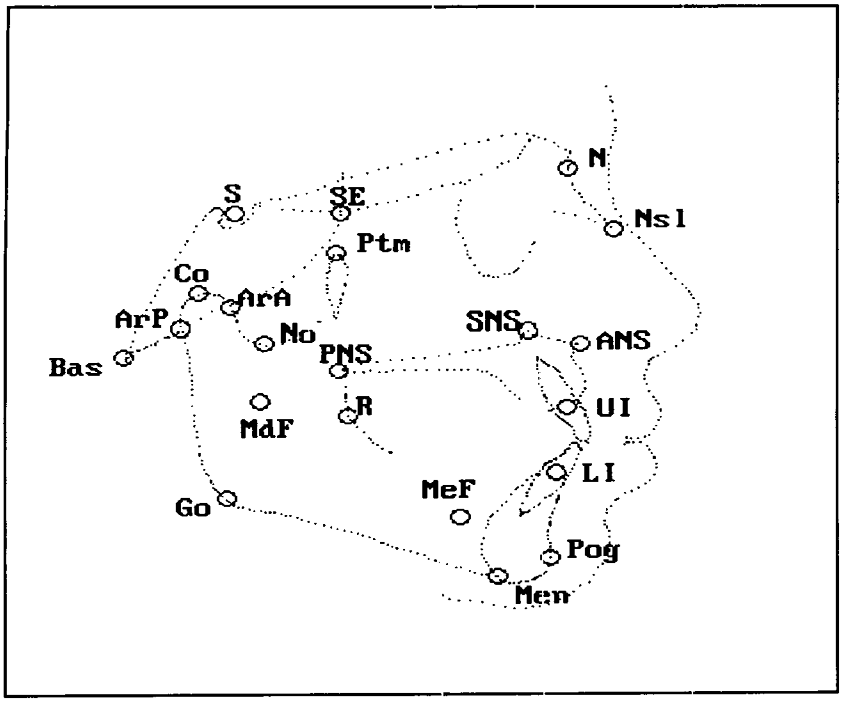

Figure 1

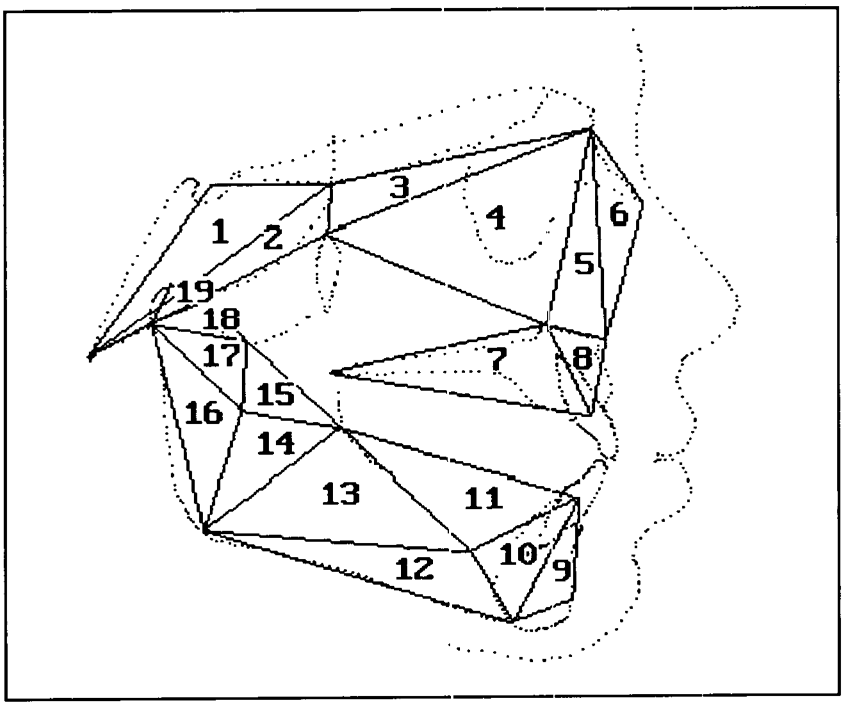

Figure 2

Figure 1
Cephalometric landmarks used as nodal points

Figure 2
Discretization of the craniofacial complex

well as many computerized methods, the clinician has a nearly limitless choice of numbers from which to select those that he or she feels are significant. In patients with unusual patterns of growth, long treatment times, or other inauspicious conditions, the same superimpositions are often used to identify other problems. Treatment can be altered to adjust for these changes or to anticipate problems in retention.

The finite element method in craniofacial research was popularized by Moss, Cheverud, and others.[5-9] Some recent approaches to orthodontic problems using the method have appeared in the literature,[10-11] but the method has been criticized for being impractical. Indeed, it must be noted that several other sophisticated mathematical approaches have been developed since finite elements were first applied to morphometrics. These newer methods, while elegant and rigorous, present the same problems: either they lack direct clinical applicability or, worse, they lack any clinical relevance at all. The science of morphometrics has advanced greatly under the aegis of Bookstein and others,[12] particularly in the statistical analysis of landmark data. However, it should not be necessary for the busy clinical orthodontist to understand the mathematics or inner workings of the software. One need only peruse the few articles in the clinical literature featuring advanced mathematical ideas to see that the reader is usually presented with a host of unfathomable (to most clinicians and orthodontic researchers) equations and geometric figures. Faced with the myriad problems of day-to-day practice, few will take the time to read these articles. The challenge to the developer, therefore, is to transform these methods into tools that are more readily accessible.

Since finite elements are appropriate for the evaluation of longitudinal data, our objective was to apply the method to serial lateral headfilms of treated orthodontic cases in a manner that could be easily understood.

Materials and methods

The key points for the user of finite elements are the selection of cephalometric landmarks as the nodal points and the way in which these points are connected to form the elements, the discretization of the form. The rationale for any nodal point and element selection must be based on sound biological and clinical reasoning. In a growth study, for example, the craniofacial complex must be discretized as completely as possible. However, the choice of replicable landmarks is the major factor limiting the choice

Table I
Nodal Points and Discretization

Element Number:	Nodal points:		
	Maxillary		
1.	Bas	S	SE
2.	Bas	Ptm	SE
3.	SE	Ptm	N
4.	N	Ptm	SNS
5.	N	SNS	ANS
6.	N	ANS	Nsl
7.	PNS	SNS	UI*
8.	SNS*	UI	ANS
	Mandibular		
9.	LI*	Pog	Men
10.	LI	MeF	Men
11.	LI	R	MeF*
12.	MeF	Go	Men
13.	R	Go	MeF
14.	MdF*	Go	R
15.	No	MdF	R
16.	ArP	Go	R
17.	ArP	MdF	No
18.	ArP	No*	ArA*
19.	ArA	Co	ArP

Notes: UI = upper incisor alveolar crest, LI = lower incisor alveolar crest, SNS = superior nasal spine, No = sigmoid notch, MeF = average mental foramen, MdF = average mandibular foramen, ArA = articulare anterior analogue to traditional articulare (ArP)

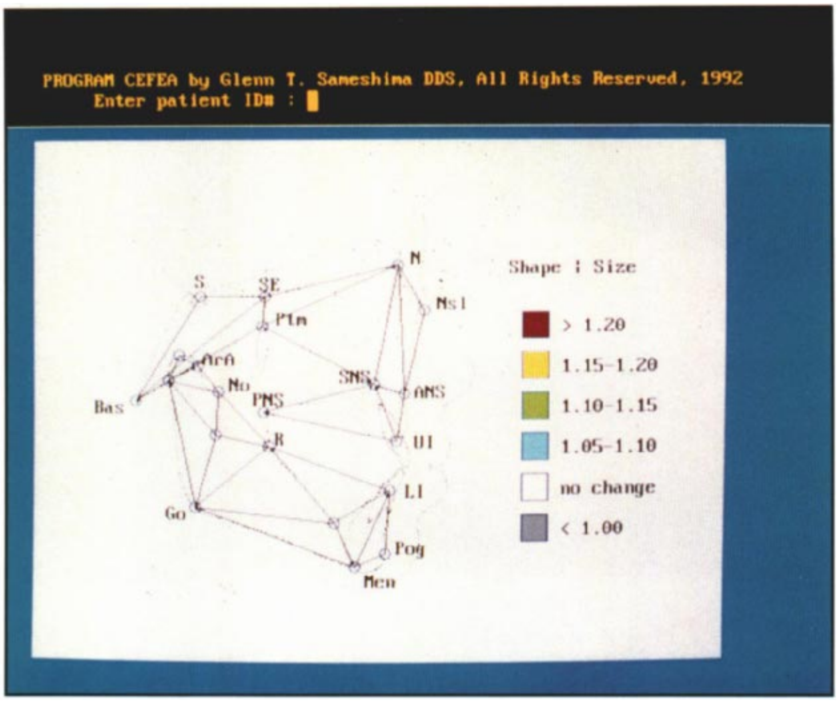

Figure 3

Figure 3
CEFEA: initial screen

of landmarks. (For example, hard tissue pogonion represents a point on bone that is subject to remodeling, but is commonly used out of clinical necessity.) However, the importance of the discretization cannot be overemphasized; the movement of landmarks with respect to each other based on experience with clinical events is the key.

The majority of studies to date employ triangles or quadrilaterals as the constituent elements. (Polygons with more sides are too complex but have been shown by McAlarney[13] to have potential value in a macroelement configuration.) The landmarks and elements used in this work are shown in Figures 1 and 2, and described in Table I. Plane triangular elements were selected for simplicity both in discretization and interpretation, while accepting the known algebraic limitations of this simple form. All finite elements eventually yield what Skalak[14] has aptly named a growth tensor. Many engineering products are possible from this tensor by convention; size ratio, shape ratio, and direction of maximum strain or dilatation, are the three used in the present work. The size ratio is the actual numerical ratio of the final area divided by the original area. If the value of this ratio is less than one, then the area of that triangle decreases over time. The shape ratio shows the difference between the maximum and minimum axes of change. The shape ratio is always greater than one. A substantial change in shape is generally greater than 1.3, although lower values may also be useful (see below). The angle change shows the direction of maximum change or distortion. Thus if one looks at this direction with respect to the three landmarks, the landmark closest to the line has moved away from the side of the triangle defined by the other two points. The directions are drawn to the Sella-Nasion line for common viewer orientation purposes only.

Our program for the finite element analysis of serial cephalometric films is called CEFEA. The program was written by G.T.S. in the simple "QuickBasic" programming language (Microsoft Corporation, Redmond, Wash) for DOS personal computers (286 or higher) and 640 X 480 VGA (16 color) screen resolution. The program is compact and RAM requirements are minimal.

Initially, the films being compared (e.g., pre- and posttreatment) are digitized and the data stored in ASCII format as two columns of Cartesian (x, y) coordinates. For maximum accuracy, the radiographs should be taken on the same

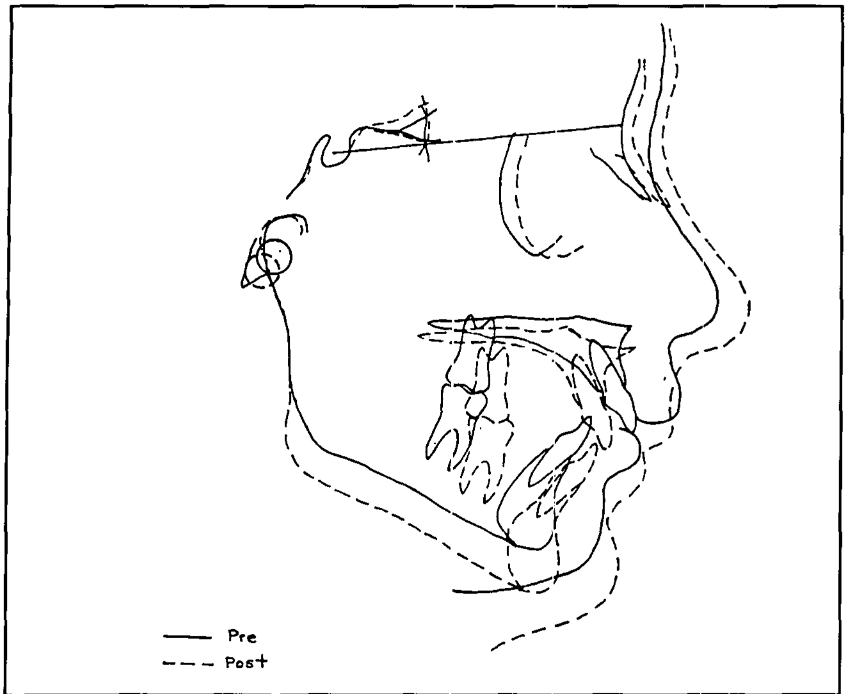

Figure 4A

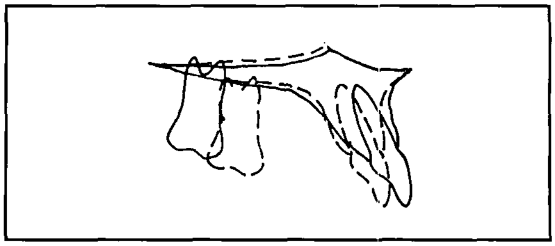

Figure 4B

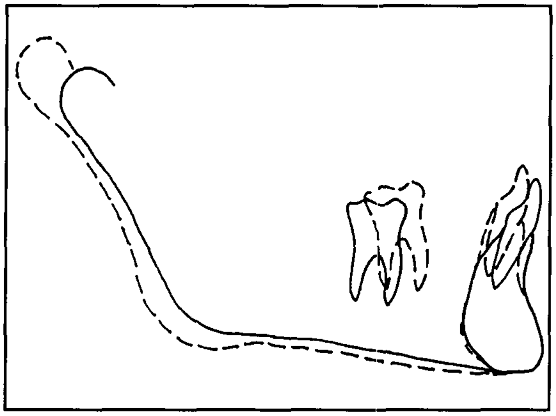

Figure 4C

Case 1
Figure 4A-C
Conventional (Steiner) posttreatment superimpositions
A: On the line sella-nasion and sella point
B: On ANS, PNS and the anterior third of the hard palate
C: On the lower border of the mandible and the mandibular symphysis

Facing page:
Figure 5
CEFEA SIZE screen

Figure 6
CEFEA SHAPE screen

Figure 7
CEFEA ANGLE of maximum change screen

machine under standardized conditions. The films may either be traced first or digitized directly. (The digitizing hardware and software used to collect the coordinates were a Scriptel digitizing tablet and Sigma-scan [Jandel Scientific, Corte Madera, Calif] software; however, the program can be modified to accommodate any digitizing tablet and a CEFEA subroutine will allow direct input into the program from the tablet.) The default choice of nodal points and triangles is shown in Figures 1 and 2. However, the user may select a custom configuration with different points and triangles. (The selection of this "meshwork" has some restrictions: long, narrow triangles should not be used and all elements ideally should have a similar initial shape. However, in practice we are constrained by the available landmarks and the need to correlate landmark movement with what we know happens clinically.)

After program initiation, the user is asked for a four-digit patient identification number. The opening screen is shown in Figure 3. A standard tracing is used to depict structures and the elements. (If the user has a file of the actual contour points of the patient, this can be used instead.) Next, the user is asked if SIZE, SHAPE or ANGLE analysis is desired. Upon entry of choice, the program displays a standard cephalometric outline with the elements outlined. Each element is filled with the color designating the degree of change found according to the scale on the right side of the display. The case number and variable letter (H for shape, Z for size, A for angle) are displayed on the bar below the working window. The next query asks whether the user wishes to continue with the same case or select a different one. The letter "Q" exits the program.

The scale for the SIZE and SHAPE variables was chosen after examination of over 200 cases.[15] A mathematical analysis was performed to determine maximal deflections beyond the usual error associated with the identification (reproducibility) of points. A size or shape ratio of 1.05 or more was determined to be greater than random error. The amount of change is of clinical and biological importance in direct proportion to the increasing values represented by the color scale boxes (see, e.g., Case One and Figures 5-7). This method permits a broad range of flexibility in selecting the scale, depending upon the type of data (e.g., length of time) input. Work in progress to analyze the population distribution of ratios will yield an increased level of quantitative rigor.

The scale for direction ranges from zero to 180 degrees. The scale does not exceed 180 degrees because the vector is bidirectional. For simplicity in coloration, the scale was limited to four divisions (see Figure 7). The scale for direction appears only when the ANGLE selection is made.

Two clinical cases will demonstrate the program with the three standard superimpositions that are typically used when submitting cases to the American Board of Orthodontics. In the first

Table II
Conventional Steiner Cephalometric Analysis
Case One

	Ref Norm	Pretx	Posttx
SNA (angle)	82	82.5	78
SNB (angle)	80	73	73.5
ANB (angle)	2	9.5	4.5
1 to NA (mm)	4	4.5	3.5
1 to NA (angle)	22	23	22
1 to NB (mm)	4	7.5	7
1 to NB (angle)	25	28.5	27
Po to NB (mm)	NA	3	3
1 to 1 (angle)	131	119	128
Occl to SN (angle)	14	20	19
GoGnSN (angle)	32	33	33
SL (mm)	51	44	43
SE (mm)	22	22.5	23

view, the entire posttreatment tracing is superimposed onto the pretreatment tracing using the line Sella-Nasion and the point S. Steiner[3] used this superimposition primarily to examine changes in mandibular position. The second superimposition places the tracings of the palate and maxillary teeth on the line ANS-PNS in order to determine incisor and molar movements. The third superimposition places the mandible on the lower border and the mandibular symphysis to evaluate general growth and incisor position. Tables for the finite element analysis listing the numerical values for size, shape, and direction have been omitted but can be called up in the program if desired.

Results

Case One is a female who was 10 years old at the beginning of a 38-month course of orthodontic treatment. Examination of the three superimpositions shows a typical Class II correction associated with a Tweed edgewise treatment strategy. The lower face dropped vertically and the mandible maintained its relationship to the maxilla (a "good grower") while growing forward (Figure 4A). The maxillary incisors were retracted while the maxillary molars tipped mesially and were extruded (Figure 4B). Figure 4C shows that the mandibular molars were extruded and advanced mesially while the mandibular incisors moved distally. They maintained the same position relative to the mandible (moved "bodily backwards"). This superimposition also implies that mandibular growth was nearly exactly in di-

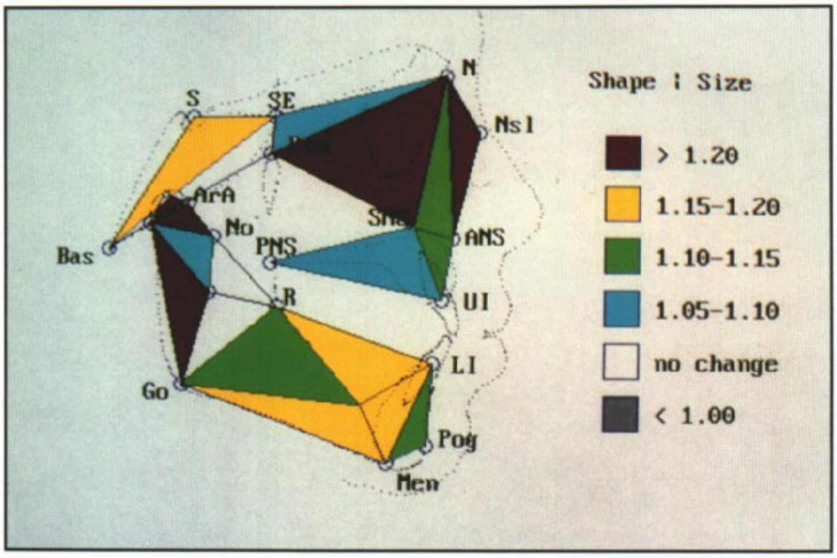

Figure 5

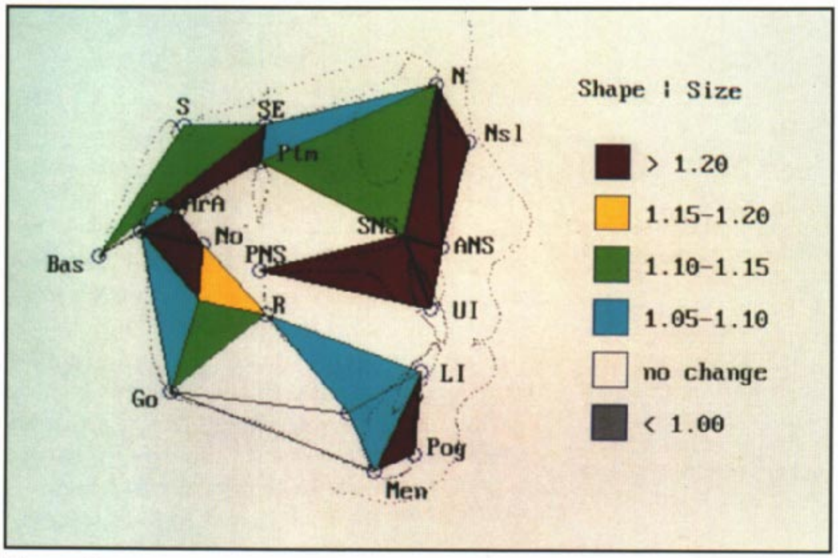

Figure 6

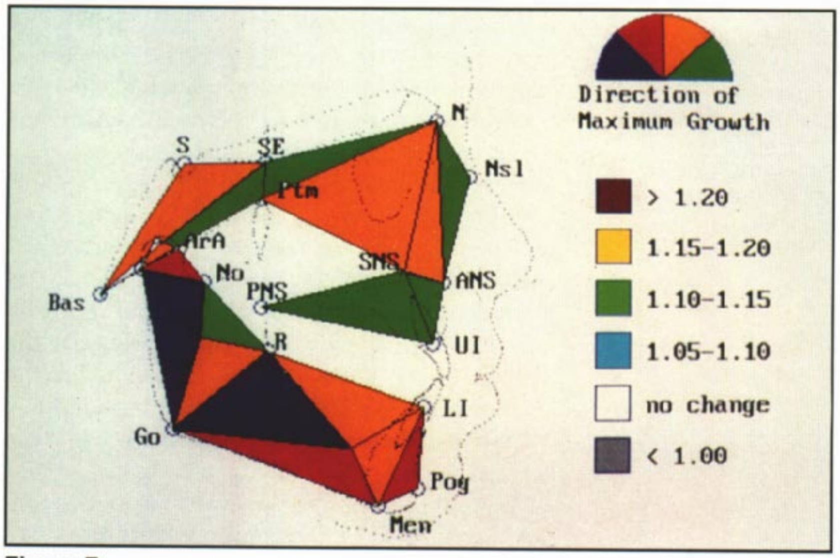

Figure 7

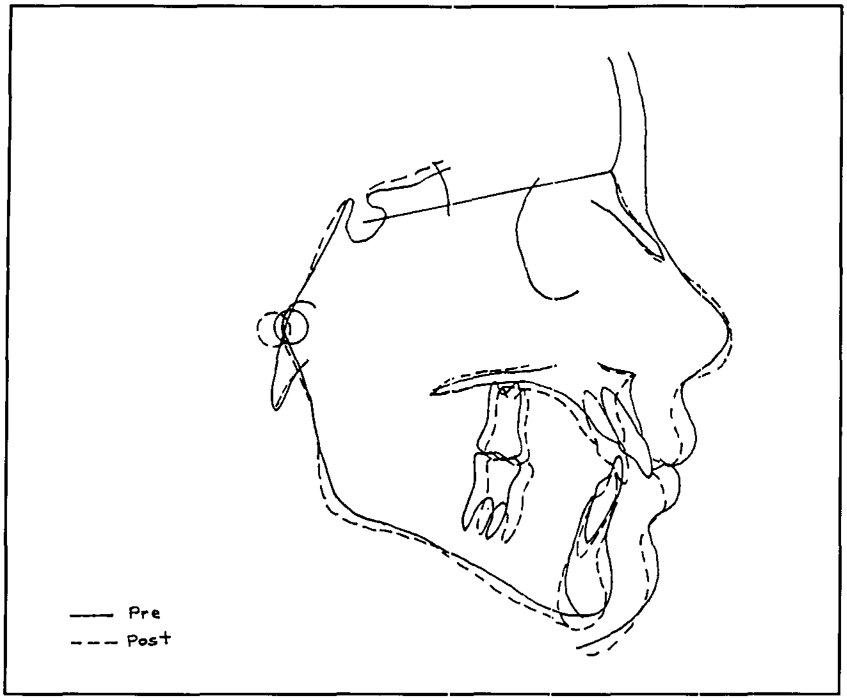

Figure 8A

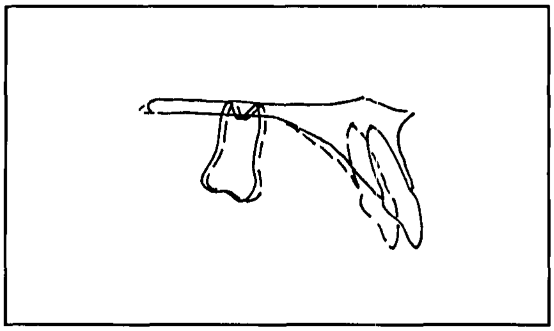

Figure 8B

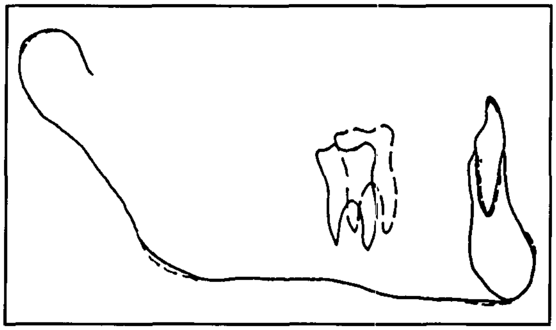

Figure 8C

Case 2

Figure 8A-C
Conventional (Steiner) posttreatment superimpositions.
A: On the line sella-nasion and sella point
B: On ANS, PNS and the anterior third of the hard palate
C: On the lower border of the mandible and the mandibular symphysis

Facing page:
Figure 9
CEFEA SIZE screen

Figure 10
CEFEA SHAPE screen

Figure 11
CEFEA ANGLE of maximum change screen

rections parallel to both the descending ramus and the inferior border of the body.

What does CEFEA tell us about this case? The color-coding system makes the variable degrees of skeletal change easy to see, and wide ranges of area are covered in Figures 5, 6, and 7. The shape display (Figure 6) demonstrates that maxillary growth was not uniform; all elements in the anterior upper face are red, signaling a major change in the relationship of these points to each other. For example, in element six (see Figure 2 for reference), the large shape and size changes demonstrate the displacement of nasale. The large shape change of the two elements sharing the node of the maxillary incisor indicate anterior segment retraction. The general lack of shape change in the mandible shows that the pattern of growth was fairly uniform. The chin element is an exception, showing large changes in shape and direction of maximum change (Figure 7). This demonstrates that the mandibular incisor and pogonion moved vertically away from each other. Absolute growth of the mandibular body appears relatively uniform by the size analysis (Figure 5); however, ramal elements, particularly near the condylar neck, show variable growth and shape change direction along the body of the mandible.

Case Two is an 11-year-old female who was treated with a standard edgewise appliance for 18 months. Four premolars were removed to alleviate crowding. Conventional superimpositions (Figure 8) show that the maxillary incisors were retracted bodily, the Class II molar relationship was corrected by advancement and extrusion of the mandibular molars, and little growth occurred during this period. A glance at the three screens from CEFEA (Figures 9-11) instantly provides the clinician with details about skeletal changes not discerned with conventional analysis. For example, the shape and size changes (Figures 9, 10) registered on the mandible are striking. It is clear that major remodeling occurred in regions not evident with the traditional superimpositions. The ANGLE screen (Figure 11) demonstrates most graphically that the direction of growth was perpendicular to the inferior and posterior borders of the mandible. Further, Nasale is seen to grow downward and forward, incisor retraction in both jaws is evident, and cranial base and most of the ramus is stable. The reduction in area of element 7 (posterior palate) is due to retraction of the maxillary incisors; note the corresponding size increase in the anterior portion.

Discussion

The CEFEA program takes advantage of the speed of personal computers without requiring expensive hardware. It uses as input only those landmarks relevant to the analysis. With the present heavy emphasis on graphics to make computers more accessible, it is natural to extend this to cephalometry, using the most advanced mathematics. The range of coverage, the speed of presentation, the simplicity of input, and the impact of the color graphics make this analysis

Table III Conventional (Steiner) Cephalometric Analysis Case Two			
	Ref Norm	Pretx	Posttx
SNA (angle)	82	83	79
SNB (angle)	80	77.5	76.5
ANB (angle)	2	5.5	2.5
1 to NA (mm)	4	5.5	4
1 to NA (angle)	22	21	23
1 to NB (mm)	4	5	5
1 to NB (angle)	25	15	18
Po to NB (mm)	NA	1.5	3
1 to 1 (angle)	131	138	137
Occl to SN (angle)	14	18	19.5
GoGnSN (angle)	32	34	36
SL (mm)	51	43.5	40
SE (mm)	22	27	27

valuable. The method has potential for use as an analysis on its own merits, but clinical trials are needed to further ascertain which parameters yield the most useful information. These trials will also establish which elements are the most important and may be used to develop a weighting scheme as suggested by Lavelle.[16] Selection of different nodal points and triangles would yield additional information. A meshwork including molar points might be more useful in determining relative dental extrusion, for example. The removal of cranial base triangles would decrease the emphasis of the present configuration on this area of the craniofacial complex. And as in traditional cephalometrics, the movement of landmarks relative to each other in midsagittal representation does not always correspond to the actual orchestration of hard tissue movement among these points. The practical use of the CEFEA program at present is as a supplemental module to a conventional package.

In summary, the user first selects SIZE to visualize where major size change occurred and to determine if the change was nearly the same for groups of related elements, e.g., body of the mandible. Next, the user accesses SHAPE to determine the pattern of craniofacial development (shape change) in the same way. Finally, the user accesses ANGLE to observe common direction with respect to known gradients, e.g., growth parallel to the body of the mandible. A control panel allows the user to switch back and forth among the three screens, or to select a different

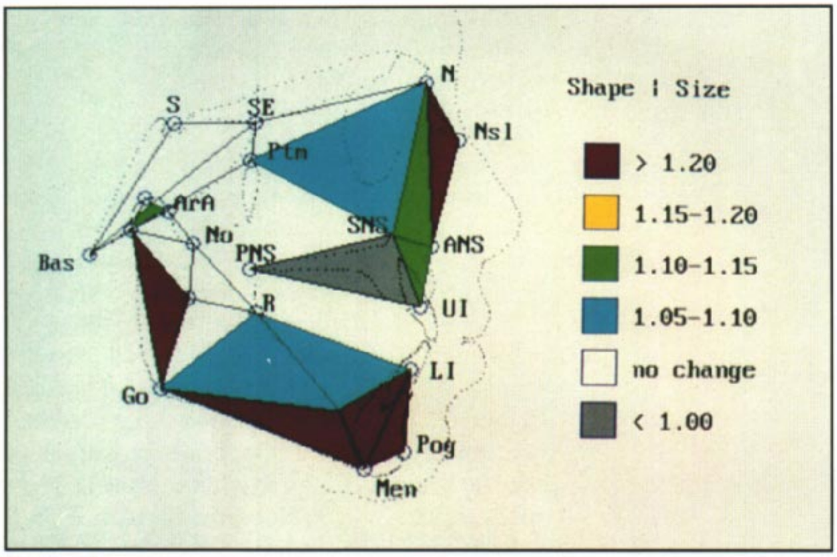

Figure 9

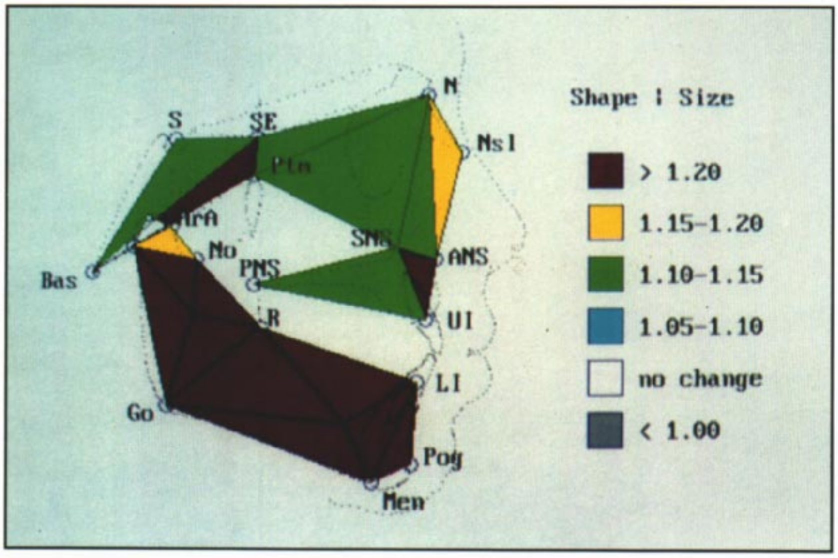

Figure 10

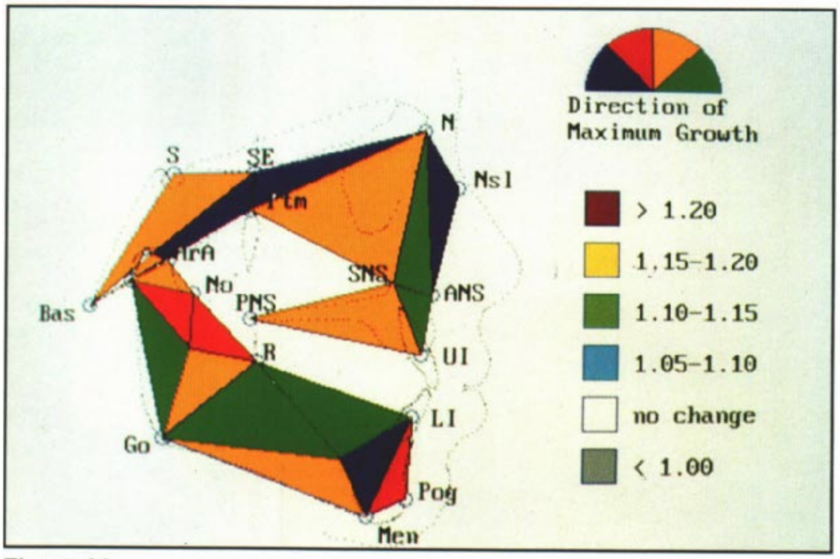

Figure 11

case at will to make a swift and meaningful assessment of the effects of treatment, either during treatment or at its completion.

Conclusions

CEFEA is a practical, clinical application of the finite element method of cephalometric analysis. It is based on sound, advanced mathematics that yield richer information than conventional, plane geometry-based analyses. Coupled with color VGA graphics on a personal computer, the speed of calculation makes the analysis interactive with immediate, powerful visualizations of skeletal change. A clear advantage is that the practitioner can immediately appreciate the areas of change without being mired in a mass of lines, angles, and overlays. Nonorthodontists, including referring dentists and patients, can also appreciate the changes so clearly evident. Thus, this tool would be valuable at a midtreatment conference, or a posttreatment evaluation. Suggestions to improve its usefulness in clinical practice are welcome. Interested parties may send the author a diskette for a stand-alone version of the program.

Finally, a secondary goal of this work was to demonstrate the introduction of a relatively complex, but valuable theoretical concept into clinical practice.

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