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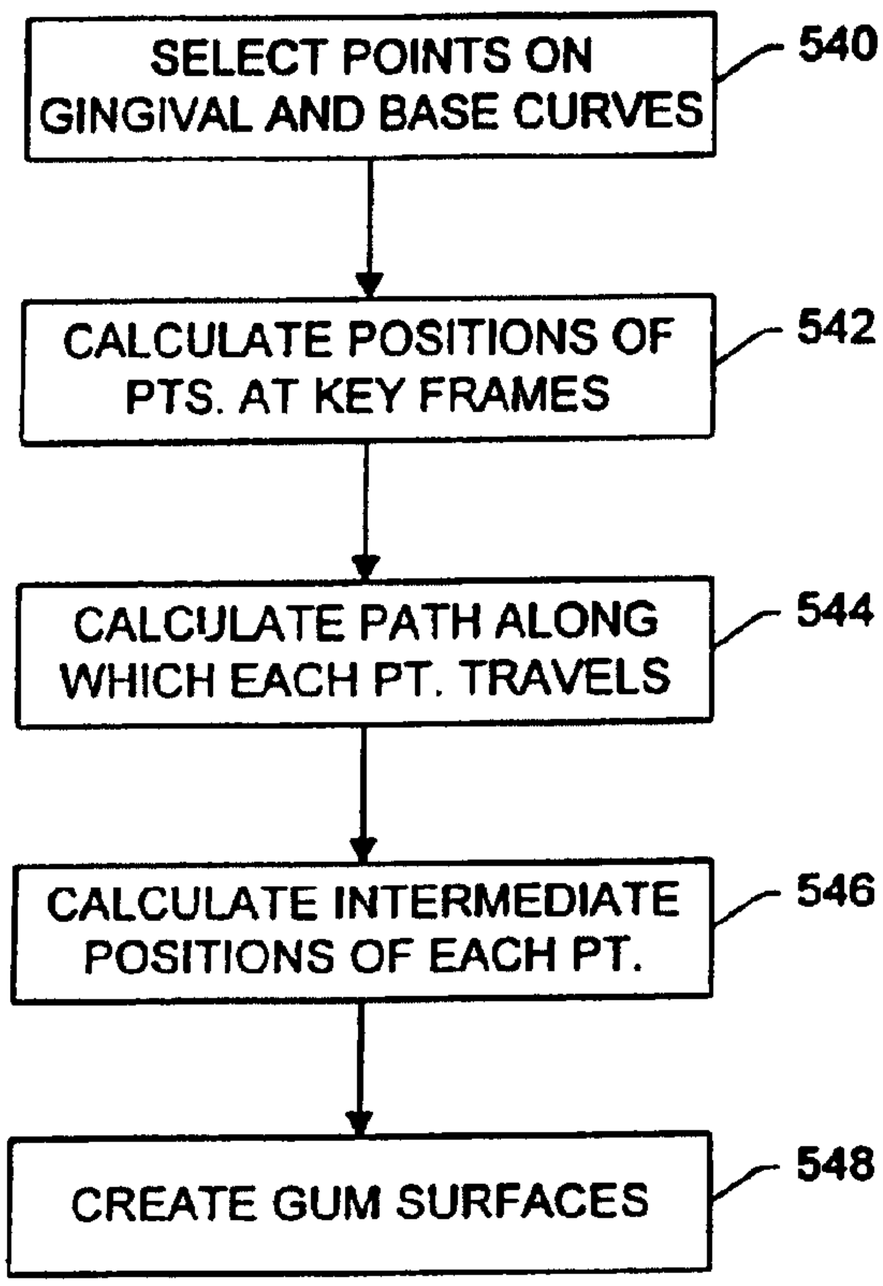
(54) Title: DIGITALLY MODELING THE DEFORMATION OF GINGIVAL TISSUE DURING ORTHODONTIC TREATMENT



(57) Abrégé/Abstract:
A computer obtains a digital model of a patient's dentition, including a dental model representing the patient's teeth at a set of initial positions, and a gingival model representing gum tissue surrounding the teeth. The computer then derives (540)(542)(544)(546)(548) from the digital model an expected deformation of the gum tissue as the teeth move from the initial positions to another set of positions.

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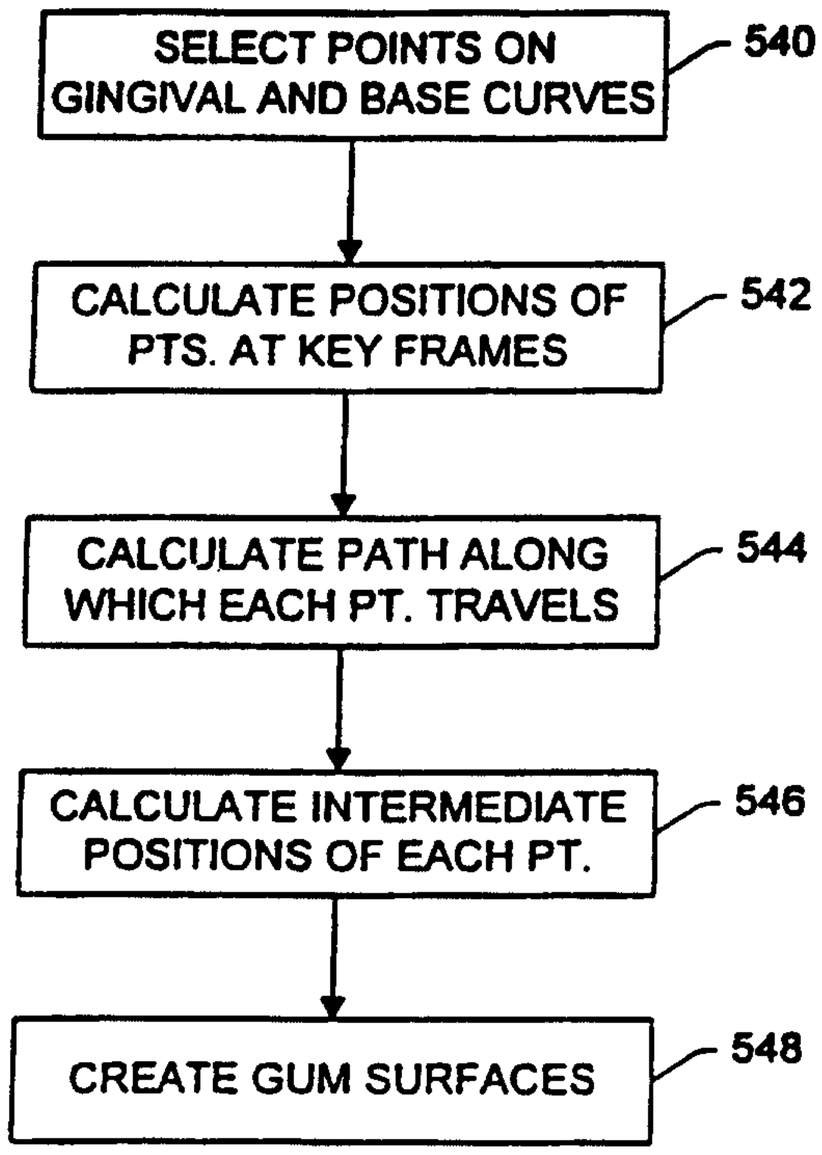
(54) Title: DIGITALLY MODELING THE DEFORMATION OF GINGIVAL TISSUE DURING ORTHODONTIC TREATMENT

(57) Abstract

A computer obtains a digital model of a patient's dentition, including a dental model representing the patient's teeth at a set of initial positions, and a gingival model representing gum tissue surrounding the teeth. The computer then derives (540, 542, 544, 546, 548) from the digital model an expected deformation of the gum tissue as the teeth move from the initial positions to another set of positions.



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DIGITALLY MODELING THE DEFORMATION OF GINGIVAL TISSUE DURING ORTHODONTIC TREATMENT

RELATED APPLICATIONS

This application is related to U.S. patent application 09/264,547, filed on March 8, 1999, and entitled "Segmenting a Digital Dentition Model," which is a continuation-in-part of U.S. patent application 09/169,276, filed on October 8, 1998, and entitled "Computer Automated Development of an Orthodontic Treatment Plan and Appliance," which claims priority from PCT application PCT/US98/12681, filed on June 19, 1998, and entitled "Method and System for Incrementally Moving Teeth," which claims priority from U.S. patent application 08/947,080, filed on October 8, 1997, which claims priority from U.S. provisional application 60/050,342, filed on June 20, 1997, all of which are incorporated by reference into this application.

This application also is related to U.S. patent application 09/311,944 filed on May 14, 1999, and entitled "Manipulating a Digital Dentition Model to Form Models of Individual Dentition Components" (attorney docket number 09943/009001); U.S. patent application 09/169,036, entitled "System and Method for Positioning Teeth"; and U.S. patent application 09/169,034, entitled "Defining Tooth-moving Appliances Computationally," all of which are incorporated by reference.

TECHNOLOGICAL FIELD

The invention relates generally to the fields of dentistry and orthodontics.

BACKGROUND

Two-dimensional (2D) and three-dimensional (3D) digital image technology has recently been tapped as a tool to assist in dental and orthodontic treatment. Many treatment providers use some form of digital image technology to study the dentitions of patients. U.S. patent application 09/169,276, incorporated by reference above, describes the use of 2D and 3D image data in forming a digital model of a patient's dentition, including models of individual dentition components. That application also describes using the digital dentition models in developing an

orthodontic treatment plan for the patient, as well as in creating one or more orthodontic appliances to implement the treatment plan.

SUMMARY

The invention provides computer-automated techniques for digitally modeling the gingival tissue of an orthodontic patient, including deformation of the gingival tissue during orthodontic treatment. These techniques are useful, for example, in creating orthodontic appliances that carry out the orthodontic treatment while fitting securely over the patient's teeth and gums. Modeling the gums and deformation of the gums helps ensure that the orthodontic appliances do not press too tightly against the patient's gums and cause discomfort or pain. Modeling how the gums react to treatment also provides a more complete understanding of what to expect during treatment. Moreover, computer-generated images and animations of the dentition during treatment are more complete and aesthetically pleasing when the gums are included.

The invention involves using a computer to develop a course of treatment for an orthodontic patient. In one aspect, the computer first obtains a digital model of a patient's dentition, including a dental model representing the patient's teeth at a set of initial positions and a gingival model representing gum tissue surrounding the teeth. The computer then derives from the digital model an expected deformation of the gum tissue as the teeth move from the initial positions to another set of positions.

In another aspect, the computer obtains a data set representing the patient's dentition, including a digital model of the patient's teeth at a set of initial positions and a first digital gingival model representing the gingival tissue surrounding the teeth at the set of initial positions. The computer then derives from the data set a second digital gingival model for use in modeling deformation of the gingival tissue as the teeth move. The computer, with or without human assistance, manipulates the second gingival model to model deformation of the patient's gums.

Other embodiments and advantages are apparent from the detailed description and the claims below.

DESCRIPTION OF THE DRAWINGS

FIGS. 1A, 1B, and 1C show the arrangement of a patient's teeth at an initial stage, an intermediate stage, and a final stage of orthodontic treatment.

FIG. 2 shows a partial model of a patient's dentition, including a model of gingival tissue.

FIG. 3 shows a model of the gum line around a tooth crown.

FIG. 4 is a flow chart of a technique for creating a secondary gingival model.

FIG. 5 illustrates the selection of control points in a digital model of the gum line of FIG. 3.

FIG. 6 illustrates the creation of two curves representing gingival margins among control points such as those shown in FIG. 5.

FIGS. 7A, 7B, and 7C illustrate the creation of a curve representing the base of a gingival model and the selection of control points on that curve.

FIG. 8 is a partial perspective view of a secondary gingival model formed by connecting the curves of FIG. 6 and the curve of FIG. 7C.

FIG. 9 is a flow chart of a technique for creating the secondary gingival model.

FIGS. 10 and 11 are graphs showing profile curves for use in forming the secondary gingival model.

FIG. 12 is a flow chart of a technique for creating gum surfaces in the secondary gingival model.

FIG. 13 shows a graphical user interface component that allows a human operator to modify the shapes of the profile curves of FIGS. 10 and 11.

FIGS. 14, 15, and 16 are a graph and flow charts illustrating one technique for modeling the deformation of gingival tissue during the course of orthodontic treatment.

FIGS. 17 is a flow chart of an alternative technique for modeling deformation of gingival tissue.

FIGS. 18A, 18B, and 19 illustrate this alternative technique.

FIGS. 20 and 21 are flow charts describing specific embodiments of this alternative technique.

DETAILED DESCRIPTION

U.S. patent applications 09/169,276, 09/264,547, and 09/311,941 (attorney docket number 009001) describe techniques for generating 3D digital data sets containing models of individual

components of a patient's dentition. These data sets include digital models of individual teeth and the gingival tissue surrounding the teeth. These applications also describe computer-implemented techniques for using the digital models in designing and simulating an orthodontic treatment plan for the patient. For example, one such technique involves receiving an initial data set that represents the patient's teeth before treatment, specifying a desired arrangement of the patient's teeth after treatment, and calculating transformations that will move the teeth from the initial to the final positions over desired treatment paths. U.S. application 09/169,276 also describes the creation of data sets representing the tooth positions at various treatment stages and the use of these data sets to produce orthodontic appliances that implement the treatment plan. One technique for producing an orthodontic appliance involves creating a positive mold of the patient's dentition at one of the treatment stages and using a conventional pressure molding technique to form the appliance around the positive mold. The design of orthodontic appliances from digital dentition models is described in U.S. application 09/169,034.

FIGS. 1A, 1B, and 1C show a patient's dentition at three stages during a course of treatment. FIG. 1A illustrates the initial positions of the patient's teeth before treatment begins. A digital model of the teeth at these initial positions is captured in an initial digital data set (IDDS). The digital model contained in the IDDS also includes portions representing gingival tissue surrounding the patient's teeth. A computer segments the IDDS into digital models of individual teeth and the gingival tissue.

FIG. 1B illustrates the patient's teeth at an intermediate stage in the treatment process, and FIG. 1C illustrates the teeth at their final positions. In many cases, a human operator manipulates the digital models of the patient's teeth to prescribe the final tooth positions. The computer then calculates one or more of the intermediate positions, taking into account any constraints imposed on the movement of the teeth by the human operator or by the natural characteristics of the teeth themselves. The computer also accounts for any collisions that might occur between teeth as the teeth move from one treatment stage to the next. Selecting the final and intermediate tooth positions and the treatment paths along which the teeth move is described in more detail in one or more of the applications incorporated by reference above.

FIG. 2 illustrates a portion of a typical digital dentition model 110 derived from the IDDS. The dentition model 110 includes models of individual teeth 120 and a model of the patient's gums 140. Various techniques for creating models of gum tissue and individual teeth from the

IDDS are described in U.S. applications 09/264,547 and 09/311,994 (attorney docket number 09943/009001).

FIG. 2 also shows a portion of a another gingival model 200 (a "secondary" gingival model), which is constructed to overlie the gingival model 140 derived from the IDDS (the "primary" gingival model). The computer uses the secondary gingival model 200, as described below, to model the deformation of the gingival tissue around the patient's teeth as the teeth move from the initial to the final positions. This ensures that orthodontic appliances made from positive molds of the patient's dentition fit comfortably around the patient's gums at all treatment stages. The secondary gingival model 200 also adds thickness to the gum model, which ensures that the orthodontic appliances do not press too tightly against the patient's gums.

FIG. 3 shows a tooth crown 125 and a corresponding gingival margin 160 around the tooth crown 125. The primary gum model 140 derived from the IDDS includes information identifying the gingival margin 160 surrounding each tooth crown 125 in the dentition model 110. The computer uses this information, as described below, to create the secondary gingival model 200 automatically.

FIGS. 4-16 illustrate one technique for creating the secondary gingival model 200. In short, a computer, under control of a program implementing one or more techniques of the invention, creates curves representing the patient's gum lines and the base of the secondary model and then creates surfaces joining these curves. These surfaces become the gum surfaces in the secondary gingival model 200.

Referring to FIGS. 4 and 5, the computer first identifies each gingival margin 160 in the dentition model (step 500) and selects points 205A-F lying on the gingival margin 160 (step 502). The computer selects at least one point lying on the buccal surface 210 of the gingival margin 160 and at least one point lying on the lingual surface 215. In the example shown here, the computer selects six points 205A-F, three on each of the buccal and lingual surfaces. One technique for selecting these six points involves projecting the gingival margin 160 onto an x-y plane, selecting the point 205A at which the gingival margin 160 intersects one axis 220 of the plane, and then selecting the remaining points 205B-F at intervals of 60° around the gingival margin 160. In some embodiments, the computer varies the interval between the selected points or allows a human operator to select the positions of the points. In many cases the computer selects more than three points, often many more than three. The selected points can serve as

control points that allow the human operator to manipulate the shape of the secondary gingival model 200, as described below.

Referring also to FIG. 6, once the computer has selected the points on each gingival margin 160, the computer uses the selected points to create two curves 230, 235 representing the gum lines on the buccal and lingual sides of the dentition model (step 504). These curves 230, 235 extend along the buccal and lingual surfaces of the teeth in the dentition model, beginning at the rear molar on one side of the patient's mouth and ending at the rear molar on the other side of the patient's mouth. The computer forms the curves by fitting one spline curve among the selected points on the buccal sides of the gingival margins and by fitting another spline curve among the selected points on the lingual sides of the gingival margins. The spline curves may or may not pass though all of the selected points from one model to the next.

Referring also to FIGS. 7A, 7B, and 7C, the computer then creates a curve 240 that defines the base of the secondary gingival model 200 (step 506). One technique for creating the base curve 240 involves creating a plane 245 that intersects the primary gingival model 140 at some predetermined distance **x** below the teeth 120. This plane 245 is usually normal to the z-axis 250 of the dentition model 110 and roughly parallel to the bottom surface 255 of the dentition model 110. The base curve 240 occurs where the plane 245 intersects the surface of the dentition model 110. The distance **x** between the plane 245 and the teeth 120 varies from model to model, but a distance on the order of one millimeter is common. FIG. 7B shows that, in some embodiments, the secondary gingival model 200 often is large enough to cover only a portion of the primary gingival model 140. In some of these embodiments, the secondary model 200 covers only the portion of the gums that come into contact with the orthodontic appliances.

The computer optionally defines control points 260 on the base curve 240 of the secondary gingival model 200 (step 508). These control points 260 allow a human operator to modify the shape of the secondary gingival model 200. In the example shown, the computer defines eight control points on each of the buccal and lingual sides of the base curve 240.

Referring also to FIG. 8, the computer completes the secondary gingival model by creating surfaces 265, 270, 275 that connect the gingival curves 230, 235 to each other and to the base curve 240 (step 510). FIG. 9 shows one technique for creating these surfaces. The computer first selects points 280A-F on each of the curves 230, 235, 240 (step 520). The computer then creates curves 285A-D between these points (step 522) and creates surface segments 290A,

290B that connect these curves (step 524). The points 280A-F selected by the computer may or may not be the control points 205A-F, 260 discussed above. Each point on one of the gingival curves 230, 235 has two corresponding points, one lying on the other gingival curve and one lying on the base curve 240. Each point on the base curve 240 has one corresponding point, which lies on the nearest one of the gingival curves 230, 235.

FIGS. 10 and 11 show profile curves 295A, 295B, 295C that are used in some cases to create the curves 285A-D of in FIG. 8. The profile curves represent the shapes of the gingival surfaces 265, 270, 275 between two corresponding points. As shown in FIG. 12, the computer inserts the profile curve 295A of FIG. 10 between pairs of points lying on the gingival curves 230, 235 to form the top surface 265 of the secondary gingival model 200 (step 530). The computer inserts the profile curves 295B, 295C of FIG. 11 between points lying on the gingival curves 230, 235 and points lying on the base curve 240 to form the buccal and lingual surfaces 270, 275 of the secondary gingival model 200 (step 536). The computer chooses one of the curves 295B, 295C of FIG. 11 based upon the type of tooth that resides in the area in which the curve is to be inserted (step 532). For example, teeth at the front of the dentition, such as incisors, typically produce less curvature in the gum surface than teeth at the rear of the dentition, such as molars and canine teeth. Therefore, the computer selects the profile curve 295B with the flatter profile to model the gum surfaces around front teeth and selects the profile curve 295C with the more rounded profile to model the gum surfaces around rear teeth.

In some embodiments, each of the profile curves 295B, 295C of FIG. 11 is associated with one type of tooth, such as a front incisor or a rear molar. In these situations, the computer creates curves for gum surfaces adjacent to other types of teeth by interpolating between the two profile curves 295A, 295B (step 534). For example, in some cases the computer averages the two profile curves 295B, 295C of FIG. 11 to create a custom curve 295D representing the gum surfaces in the vicinity of a bicuspid. Other alternatives include storing a unique profile curve for each tooth or each type of tooth in the dentition model.

The computer also allows a human operator to adjust the shapes of the profile curves, and thus the gum surfaces, in some embodiments (step 538). FIG. 13 shows a graphical user interface component, in the form of a slide bar 300, that allows the operator to adjust the curvature of each of the profile curves 295A, 295B, 295C. Adjusting the position of the slide element 305 in the slide bar 300 changes the tangent vectors along the profile curves, which in

turn changes the shapes of the curves. Other alternatives include placing control points along the curves and allowing the human operator to adjust the positions of the control points.

FIGS. 14 and 15 show how the secondary gingival model 200 is used to model deformation of the gum tissue during the treatment process. As described in U.S. application 09/169,276, incorporated by reference above, the computer, either with or without human assistance, creates models of the patient's teeth at key treatment stages, known as key frames, between the initial and final positions. The computer also derives treatment paths along which the patient's teeth will move in going from the initial to the final positions. The treatment paths include both translational and rotational components that create the forces necessary to move the teeth to the desired positions. The treatment path for each tooth fits among the desired tooth positions at each of key frames but need not actually pass through all of the desired positions at the key frames. Models of the patient's dentition at various intermediate stages along the treatment path are used to create the orthodontic appliances that carry out the treatment plan.

In modeling gum deformation, the computer selects one or more points 310 along the gingival curves 230, 235 and the base curve 240 of the secondary gingival model (step 540) and calculates the positions of each point 310 at the initial and final stages S_O, S_F and at each of the key intermediate stages S_{Ix}, or key frames (step 542). In most cases, the points selected by the computer are the control points described above. The computer then calculates a path 315 along which the point 310 will travel. In general, the path 315 follows the curvature of the tooth that is closest to the point 310 in the dentition model. The computer determines the position of the point 310 at any given intermediate stage by the interpolating linearly along the path 315. For example, for a treatment plan in which the initial stage is Stage 1 and the first key frame occurs at Stage 10, the position of the point 310 at intermediate Stage 5 is the midpoint of the curved path 315 between Stage 1 and Stage 10. The computer generates gingival models at each of these stages by inserting profile curves and surfaces as described above.

FIG. 16 illustrates one technique for calculating the positions of the selected points on the gum lines at the key frames. This technique assumes that the selected points travel with the teeth from the initial positions to final positions. The computer first identifies the tooth closest to each point (step 550). The computer then monitors the transformations applied to each tooth in moving the tooth among the key stages to its final position (step 552). The computer applies these transformations to the corresponding points on the gum lines (step 554).

FIGS. 17, 18A, and 8B illustrate another technique for modeling the deformation of gum tissue. This technique involves dividing the secondary gingival model 200 into multiple pieces 320, 325, 330 by cutting very thin slices 335, 340 in the secondary gingival model 200 between pairs of adjacent teeth 345/350, 345/355 (step 560). Dividing the gingival model 200 in this manner allows one or more of the pieces 320, 325, 330 to move with a corresponding tooth 345, 350, 355. This technique is used most commonly to model the deformation of gum tissue around teeth that move relatively little between two treatment stages.

For each piece 320 of the secondary gum model that is to move with a tooth 345, the computer "attaches" the piece 320 to the digital model of the tooth 345 (step 562). The computer monitors the transformations applied to the tooth 345 (step 564) and applies each of these transformations to the attached piece 320 of the gingival model (step 566). As the piece 320 of the gingival model 200 moves with the tooth model, the slices 335, 340 between the pieces 320, 325, 330 of the gum model 200 grow in size, creating gaps between the pieces. When the piece 320 finally is detached from the corresponding tooth model (step 568), the computer "stitches" the secondary gingival model 200 by creating surfaces 360, 365 to fill the gaps (step 570).

FIGS. 19 and 20 show one technique for creating a stitching surface 400 in the secondary gingival model 200. For each slice 335 to be stitched, the computer selects points 380 on the edges 370, 375 of the two pieces 320, 325 that bound the slice 335 (step 580). The computer then creates line segments 385 to form triangles bounded by the selected points 380 (step 582). Each of the triangles is bounded by two points on one of the edges 370, 375 and one point on the other edge. The computer then divides each triangle into four smaller triangles by selecting points 390 at or near the centers of the line segments 390 and creating smaller line segments 395 that extend between pairs of the newly selected points 390 (step 384). The result is a triangular surface mesh in which each point that does not lie on one of the edges 370, 375 (each "center vertex") is shared by six of the smaller triangles. For example, the center vertex labeled 405B is shared by the six smaller triangles labeled T1, T2, T3, T4, T5, T6. Each vertex that lies on one of the edges 370, 375 is shared by three of the smaller triangles.

In some embodiments, the computer adjusts the shape of the stitching surface 400 by moving the center vertices 405A, 405B, 405C in a direction that is roughly normal to the stitching surface 400 (step 586). FIG. 21 illustrates one technique for adjusting the curvature of the stitching surface 400. The computer first calculates the normals for the six triangles that

share each center vertex 405A, 405B, 405C (step 590). The computer then averages these normals to find an "average normal" at the center vertex (step 592). The computer then moves the center vertex along the average normal by a selected amount (step 594). In some cases, the computer receives instructions from a human operator to adjust the shape of the stitching surface in a certain manner (step 596). For example, one embodiment displays the center vertices as control points, which the user manipulates with an input device such as a mouse.

Some implementations of the invention are realized in digital electronic circuitry, such as an application specific integrated circuit (ASIC); others are realized in computer hardware, firmware, and software, or in combinations of digital circuitry and computer components. The invention is usually embodied, at least in part, as a computer program tangibly stored in a machine-readable storage device for execution by a computer processor. In these situations, methods embodying the invention are performed when the processor executes instructions organized into program modules, operating on input data and generating output. Suitable processors include general and special purpose microprocessors, which generally receive instructions and data from read-only memory and/or random access memory devices. Storage devices that are suitable for tangibly embodying computer program instructions include all forms of non-volatile memory, including semiconductor memory devices, such as EPROM, EEPROM, and flash memory devices; magnetic disks such as internal hard disks and removable disks; magneto-optical disks; and CD-ROM.

The invention has been described in terms of particular embodiments. Other embodiments are within the scope of the following claims.

CLAIMS

1. A computer-implemented method for use in developing a course of treatment for an orthodontic patient, the method comprising:

obtaining a digital model of a patient's dentition, including a dental model representing the patient's teeth at a set of initial positions and a gingival model representing gum tissue surrounding the teeth; and

deriving from the digital model an expected deformation of the gum tissue as the teeth move from the initial positions to another set of positions.

2. The method of claim 1, wherein deriving the expected deformation of the gum tissue includes:

separating from the gingival model a portion that represents gum tissue surrounding a particular tooth; and

subjecting the separated portion to at least one force that is applied to the particular tooth.

3. The method of claim 2, further comprising reconnecting the separated portion to an adjacent portion of the gingival model after subjecting the separated portion to the transformation.

4. The method of claim 3, wherein subjecting the separated portion to at least one force creates a gap between the separated portion and the adjacent portion of the gingival model, and wherein reconnecting the separated portion to the adjacent portion includes creating a stitching surface to fill the gap.

5. The method of claim 4, further comprising adjusting the shape of the stitching surface to alter the shape of the gum tissue in the reconnected gingival model.

6. The method of claim 5, wherein adjusting the shape of the stitching surface includes receiving instructions from a human operator concerning the shape of the stitching surface.

7. The method of claim 5, wherein adjusting the shape of the stitching surface includes automatically applying a rule without human intervention.

8. The method of claim 4, wherein the stitching surface is bounded by two curves representing edges of the separated portion and the adjacent portion of the gingival model.

9. The method of claim 8, wherein creating the stitching surface includes:

selecting points on the curves; and

connecting the points to form triangles representing a surface mesh.

10. The method of claim 9, further comprising adjusting the shape of the surface mesh by moving a vertex shared by multiple ones of the triangles along a line.

11. The method of claim 10, wherein moving the vertex includes:

calculating a normal line for each of the triangles that share the vertex; and

calculating an average of the normal lines.

12. The method of claim 9, further comprising dividing each of the triangles into smaller triangles to form a fine surface mesh.

13. The method of claim 12, wherein dividing the triangles includes dividing the triangles such that each of the smaller triangles has at least one vertex shared by five more of the smaller triangles.

14. The method of claim 1, wherein deriving an expected deformation of the gum tissue includes:

selecting a point in the gingival model; and

deriving motion of the point as the teeth move from the initial set of positions to the other set of positions.

15. The method of claim 14, wherein deriving motion of the point includes attaching the point to a model of a corresponding tooth in the dental model and subjecting the point to transformations applied to the corresponding tooth.

16. The method of claim 14, wherein the point lies on a gingival margin, at which the gum tissue meets one of the teeth.

17. The method of claim 14, further comprising creating another gingival model representing the gum tissue surrounding the teeth at the other set of positions.

18. The method of claim 17, wherein creating another gingival model includes:

selecting points in the gingival model;

deriving positions for the points when the teeth are at the other set of positions; and

creating a curve that connects the points at the derived positions.

19. The method of claim 18, wherein creating the curve includes selecting the curve from a group of curves that have predetermined profiles.

20. The method of claim 19, wherein selecting the curve includes:

determining which type of tooth is nearest the points in the dentition model; and

selecting a curve associated with the type of tooth that is nearest the points.

21. The method of claim 18, wherein creating the curve includes interpolating between two curves having predetermined shapes.

22. The method of claim 18, further comprising receiving an instruction from a human operator to modify the shape of the curve.

23. A computer-implemented method for use in developing a digital model of gingival tissue in an orthodontic patient's dentition, the method comprising:

obtaining a data set representing a patient's dentition, including a digital model of the patient's teeth at a set of initial positions and a first digital gingival model representing the gingival tissue surrounding the teeth at the set of initial positions; and

deriving from the data set a second digital gingival model for use in modeling deformation of the gingival tissue as the teeth move.

24. The method of claim 23, wherein the second gingival model initially represents the gingival tissue surrounding the teeth at the set of initial positions.

25. The method of claim 24, wherein the second gingival model overlies a portion of the first gingival model so that the first and second gingival models together form a digital representation of the gingival tissue that is larger than the gingival tissue itself.

26. The method of claim 23, wherein deriving the second gingival model includes:

obtaining, for at least some teeth in the patient's dentition, data representing gingival margins, each of which surrounds a corresponding one of the teeth; and

deriving from the data a model of two gingival lines extending along buccal and lingual sides of the teeth.

27. The method of claim 26, wherein deriving the model of the two gingival lines includes selecting points on each gingival margin, including at least one lying on the buccal side of the corresponding tooth and at least one lying on the lingual side of the corresponding tooth.

28. The method of claim 27, wherein deriving the model of the two gingival lines includes fitting one curve among the points selected on the buccal side of the teeth and fitting another curve among the points selected on the lingual side of the teeth.

29. The method of claim 26, wherein deriving the second gingival model includes selecting elements of the data set that define a bottom surface of the second gingival model.

30. The method of claim 29, wherein deriving the second gingival model includes creating surfaces that connect the two gingival lines to the bottom surface.

31. The method of claim 30, wherein creating the surfaces includes creating curves that connect points on the gingival lines to points on the bottom surface.

32. The method of claim 31, wherein creating curves includes selecting profile curves that each have a predetermined shape and inserting the profile curves between the points on the gingival lines and the bottom surface.

33. The method of claim 32, wherein selecting the profile curves includes selecting at least one of the profile curves from a group of predetermined profile curves based on a type of tooth that is to lie nearest the profile curve upon inserting the profile curve into the second gingival model.

34. The method of claim 32, wherein selecting the profile curves includes creating at least one of the profile curves by interpolating between two profile curves having predetermined shapes.

35. The method of claim 31, further comprising receiving an instruction from a human operator to modify the shape of at least one of the curves inserted into the second gingival model.

36. The method of claim 26, wherein deriving the second gingival model includes creating a surface that connects the two gingival lines to each other.

37. The method of claim 36, wherein creating the surface includes creating curves that connect points lying on the two gingival lines.

38. The method of claim 37, wherein creating the curves includes selecting profile curves that each have a predetermined shape and inserting the profile curves between the points on the two gingival lines.

39. The method of claim 37, further comprising receiving an instruction from a human operator to modify the shape of at least one of the curves inserted into the second gingival model.

40. The method of claim 23, further comprising placing control points in the second gingival model and receiving an instruction from a human operator to move at least one of the control points.

41. The method of claim 40, wherein placing the control points in the second gingival model includes creating control points that lie on gingival margins surrounding the teeth.

42. The method of claim 41, wherein creating the control points includes, for each gingival margin that surrounds one of the teeth, spacing the control points at predetermined intervals along the gingival margin.

43. The method of claim 42, wherein spacing the control points includes placing the control points at equal intervals of approximately 60°.

44. The method of claim 40, wherein placing the control points in the second gingival model includes creating control points that lie on a bottom surface of the second gingival model.

45. A computer program, stored on a tangible storage medium, for use in developing a course of treatment for an orthodontic patient, the program comprising executable instructions that, when executed by a computer, cause the computer to:

obtain a digital model of a patient's dentition, including a dental model representing the patient's teeth at a set of initial positions and a gingival model representing gum tissue surrounding the teeth; and

derive from the digital model an expected deformation of the gum tissue as the teeth move from the initial positions to another set of positions.

46. The program of claim 45, wherein the computer derives the expected deformation of the gum tissue by:

separating from the gingival model a portion that represents gum tissue surrounding a particular tooth; and

subjecting the separated portion to at least one force that is applied to the particular tooth.

47. The program of claim 46, wherein the computer reconnects the separated portion to an adjacent portion of the gingival model after subjecting the separated portion to the transformation.

48. The program of claim 47, wherein, in subjecting the separated portion to at least one force, the computer creates a gap between the separated portion and the adjacent portion of the gingival model, and, in reconnecting the separated portion to the adjacent portion, the computer creates a stitching surface to fill the gap.

49. The program of claim 48, wherein the computer adjusts the shape of the stitching surface to alter the shape of the gum tissue in the reconnected gingival model.

50. The program of claim 49, wherein, in adjusting the shape of the stitching surface, the computer receives instructions from a human operator concerning the shape of the stitching surface.

51. The program of claim 48, wherein the stitching surface is bounded by two curves representing edges of the separated portion and the adjacent portion of the gingival model.

52. The program of claim 51, wherein, in creating the stitching surface, the computer selects points on the curves and connects the points to form triangles representing a surface mesh.

53. The program of claim 52, wherein the computer adjusts the shape of the surface mesh by moving a vertex shared by multiple ones of the triangles along a line.

54. The program of claim 53, wherein, in moving the vertex, the computer calculates a normal line for each of the triangles that share the vertex and calculates an average of the normal lines.

55. The program of claim 52, wherein the computer divides each of the triangles into smaller triangles to form a fine surface mesh.

56. The program of claim 55, wherein the computer divides the triangles such that each of the smaller triangles has at least one vertex shared by five more of the smaller triangles.

57. The program of claim 45, wherein, in deriving an expected deformation of the gum tissue, the computer selects a point in the gingival model and derives motion of the point as the teeth move from the initial set of positions to the other set of positions.

58. The program of claim 57, wherein, in deriving motion of the point, the computer attaches the point to a model of a corresponding tooth in the dental model and subjects the point to transformations applied to the corresponding tooth.

59. The program of claim 57, wherein the point lies on a gingival margin, at which the gum tissue meets one of the teeth.

60. The program of claim 57, wherein the computer creates another gingival model representing the gum tissue surrounding the teeth at the other set of positions.

61. The program of claim 60, wherein, in creating another gingival model, the computer selects points in the gingival model, derives positions for the points when the teeth are at the other set of positions, and creates a curve that connects the points at the derived positions.

62. The program of claim 61, wherein, in creating the curve, the computer selects the curve from a group of curves that have predetermined profiles.

63. The program of claim 62, wherein, in selecting the curve, the computer determines which type of tooth is nearest the points in the dentition model and selects a curve associated with the type of tooth that is nearest the points.

64. The program of claim 61, wherein, in creating the curve, the computer interpolates between two curves having predetermined shapes.

65. The program of claim 61, wherein the computer receives an instruction from a human operator to modify the shape of the curve.

66. A computer program, stored on a tangible storage medium, for use in developing a digital model of gingival tissue in an orthodontic patient's dentition, the program comprising executable instructions that, when executed by a computer, cause the computer to:

obtain a data set representing a patient's dentition, including a digital model of the patient's teeth at a set of initial positions and a first digital gingival model representing the gingival tissue surrounding the teeth at the set of initial positions; and

derive from the data set a second digital gingival model for use in modeling deformation of the gingival tissue as the teeth move.

67. The program of claim 66, wherein the computer creates the second gingival model to represent the gingival tissue surrounding the teeth at the set of initial positions.

68. The program of claim 67, wherein the computer creates the second gingival model to overlie a portion of the first gingival model so that the first and second gingival models together form a digital representation of the gingival tissue that is larger than the gingival tissue itself.

69. The program of claim 66, wherein, in deriving the second gingival model, the computer:

obtains, for at least some teeth in the patient's dentition, data representing gingival margins, each of which surrounds a corresponding one of the teeth; and

derives from the data a model of two gingival lines extending along buccal and lingual sides of the teeth.

70. The program of claim 69, wherein, in deriving the model of the two gingival lines, the computer selects points on each gingival margin, including at least one lying on the buccal side of the corresponding tooth and at least one lying on the lingual side of the corresponding tooth.

71. The program of claim 70, wherein, in deriving the model of the two gingival lines, the computer fits one curve among the points selected on the buccal side of the teeth and fits another curve among the points selected on the lingual side of the teeth.

72. The program of claim 69, wherein, in deriving the second gingival model, the computer selects elements of the data set that define a bottom surface of the second gingival model.

73. The program of claim 72, wherein, in deriving the second gingival model, the computer creates surfaces that connect the two gingival lines to the bottom surface.

74. The program of claim 73, wherein, in creating the surfaces, the computer creates curves that connect points on the gingival lines to points on the bottom surface.

75. The program of claim 74, wherein, in creating curves, the computer selects profile curves that each have a predetermined shape and inserts the profile curves between the points on the gingival lines and the bottom surface.

76. The program of claim 75, wherein, in selecting the profile curves, the computer selects at least one of the profile curves from a group of predetermined profile curves based on a type

of tooth that is to lie nearest the profile curve upon inserting the profile curve into the second gingival model.

77. The program of claim 75, wherein, in selecting the profile curves, the computer creates at least one of the profile curves by interpolating between two profile curves having predetermined shapes.

78. The program of claim 74, wherein the computer receives an instruction from a human operator to modify the shape of at least one of the curves inserted into the second gingival model.

79. The program of claim 69, wherein, in deriving the second gingival model, the computer creates a surface that connects the two gingival lines to each other.

80. The program of claim 79, wherein, in creating the surface, the computer creates curves that connect points lying on the two gingival lines.

81. The program of claim 80, wherein, in creating the curves, the computer selects profile curves that each have a predetermined shape and inserts the profile curves between the points on the two gingival lines.

82. The program of claim 80, wherein the computer receives an instruction from a human operator to modify the shape of at least one of the curves inserted into the second gingival model.

83. The program of claim 66, wherein the computer places control points in the second gingival model and receives an instruction from a human operator to move at least one of the control points.

84. The program of claim 83, wherein, in placing the control points in the second gingival model, the computer creates control points that lie on gingival margins surrounding the teeth.

85. The program of claim 84, wherein, in creating the control points, the computer, for each gingival margin that surrounds one of the teeth, spaces the control points at predetermined intervals along the gingival margin.

86. The program of claim 85, wherein the computer places the control points at equal intervals of approximately 60°.

87. The program of claim 83, wherein, in placing the control points in the second gingival model, the computer creates control points that lie on a bottom surface of the second gingival model.

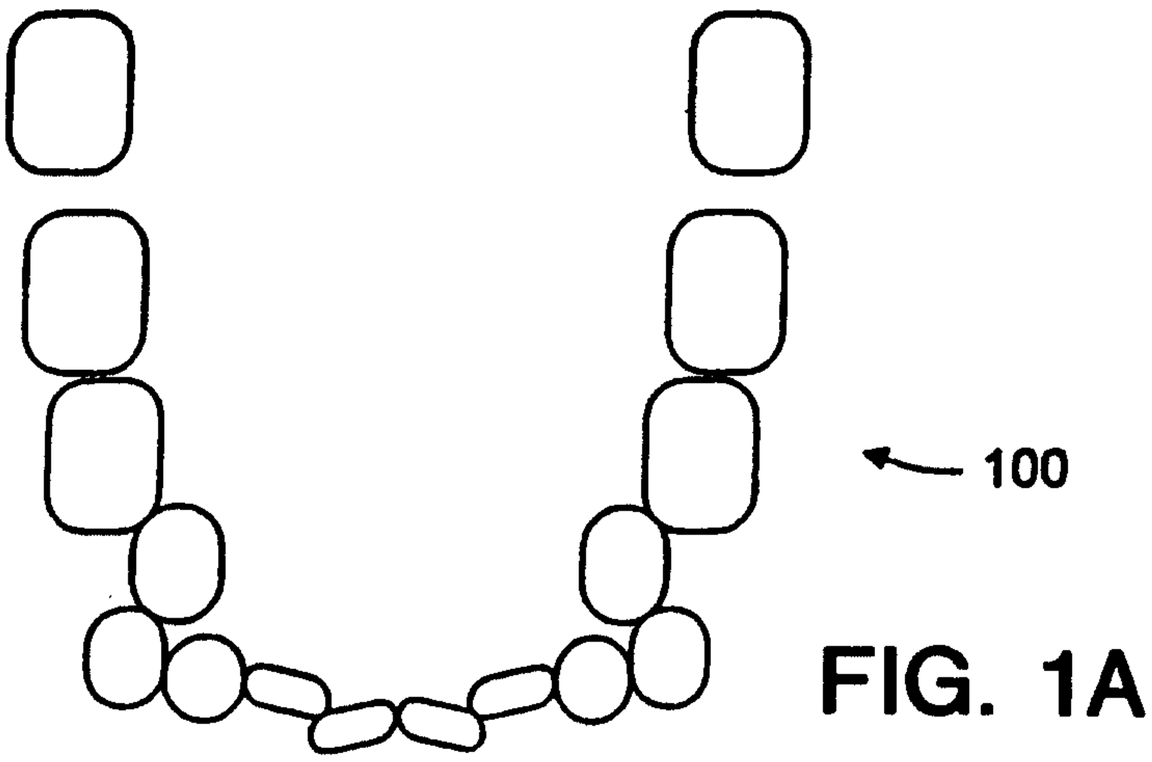


FIG. 1A

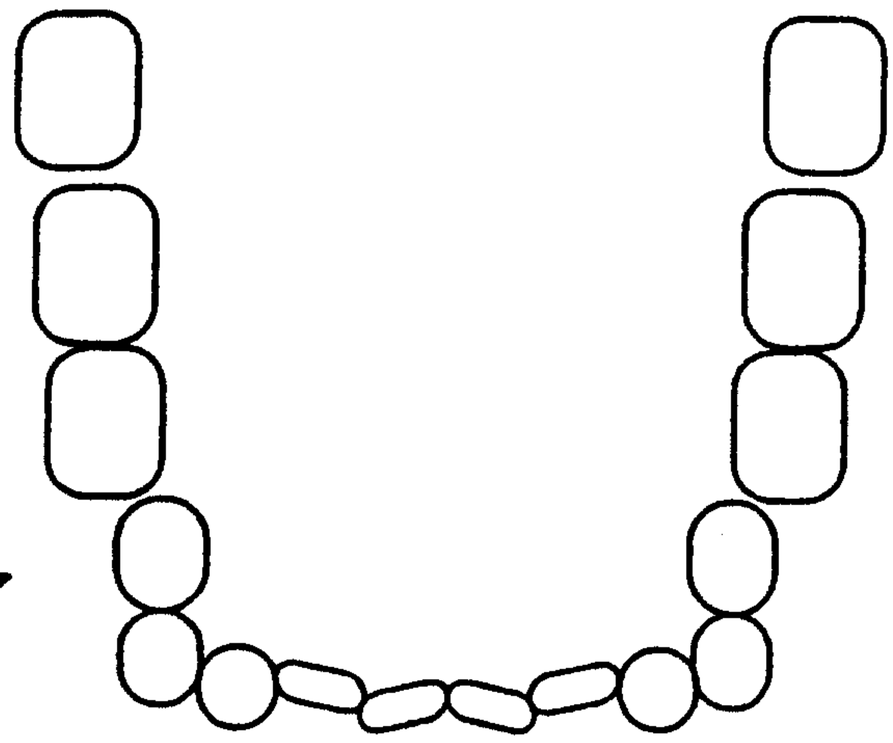


FIG. 1B

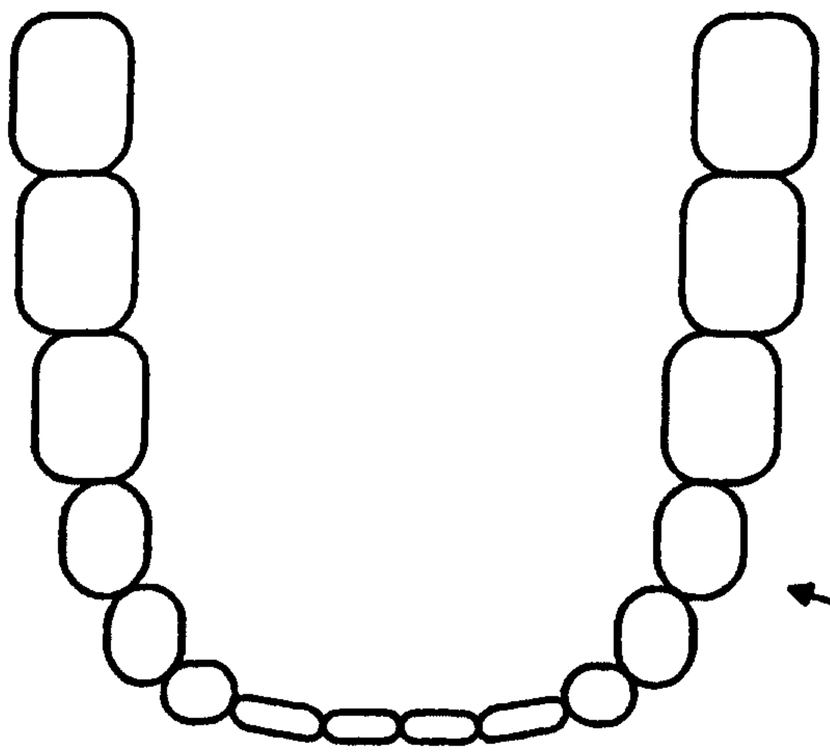


FIG. 1C

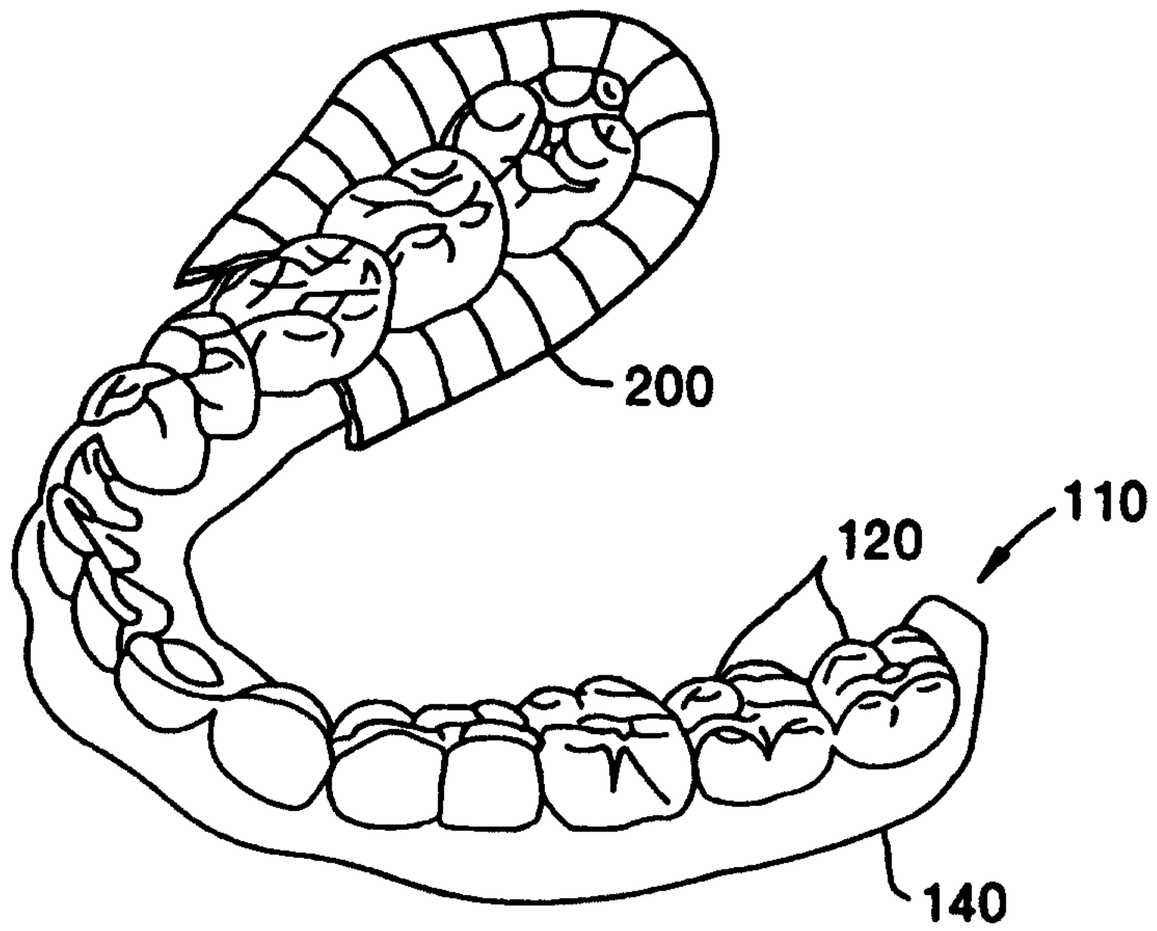


FIG. 2

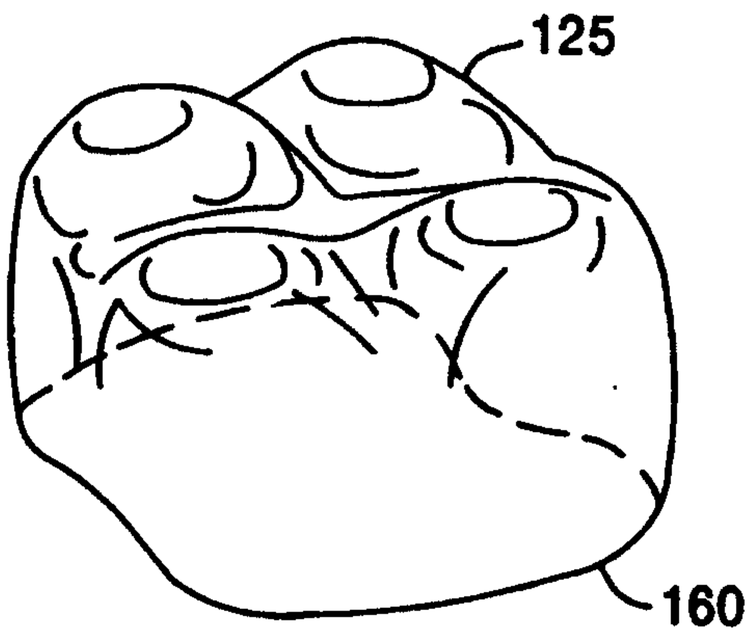


FIG. 3

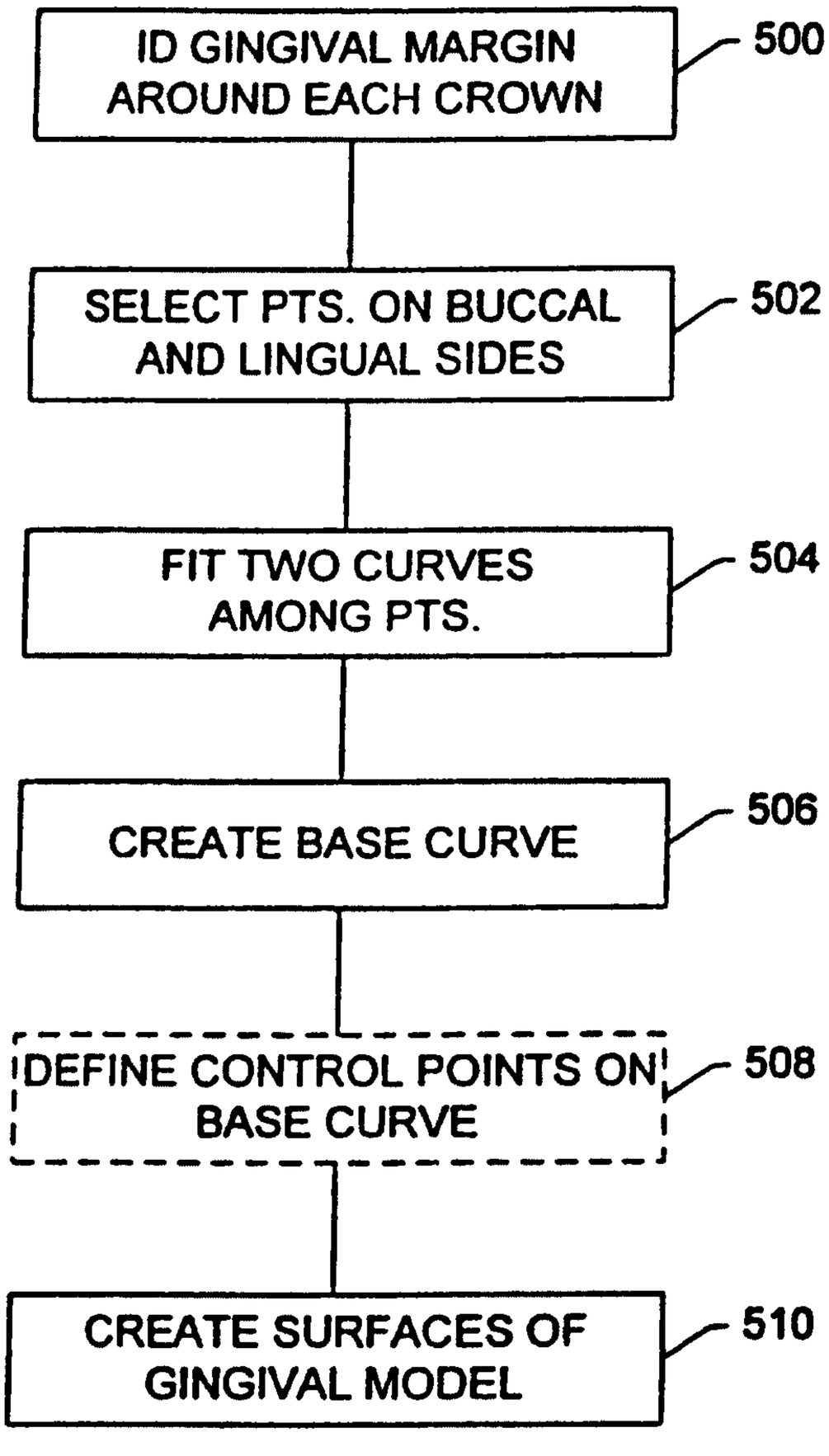

ID GINGIVAL MARGIN AROUND EACH CROWN
500
SELECT PTS. ON BUCCAL AND LINGUAL SIDES
502
FIT TWO CURVES AMONG PTS.
504
CREATE BASE CURVE
506
DEFINE CONTROL POINTS ON BASE CURVE
508
CREATE SURFACES OF GINGIVAL MODEL
510

FIG. 4

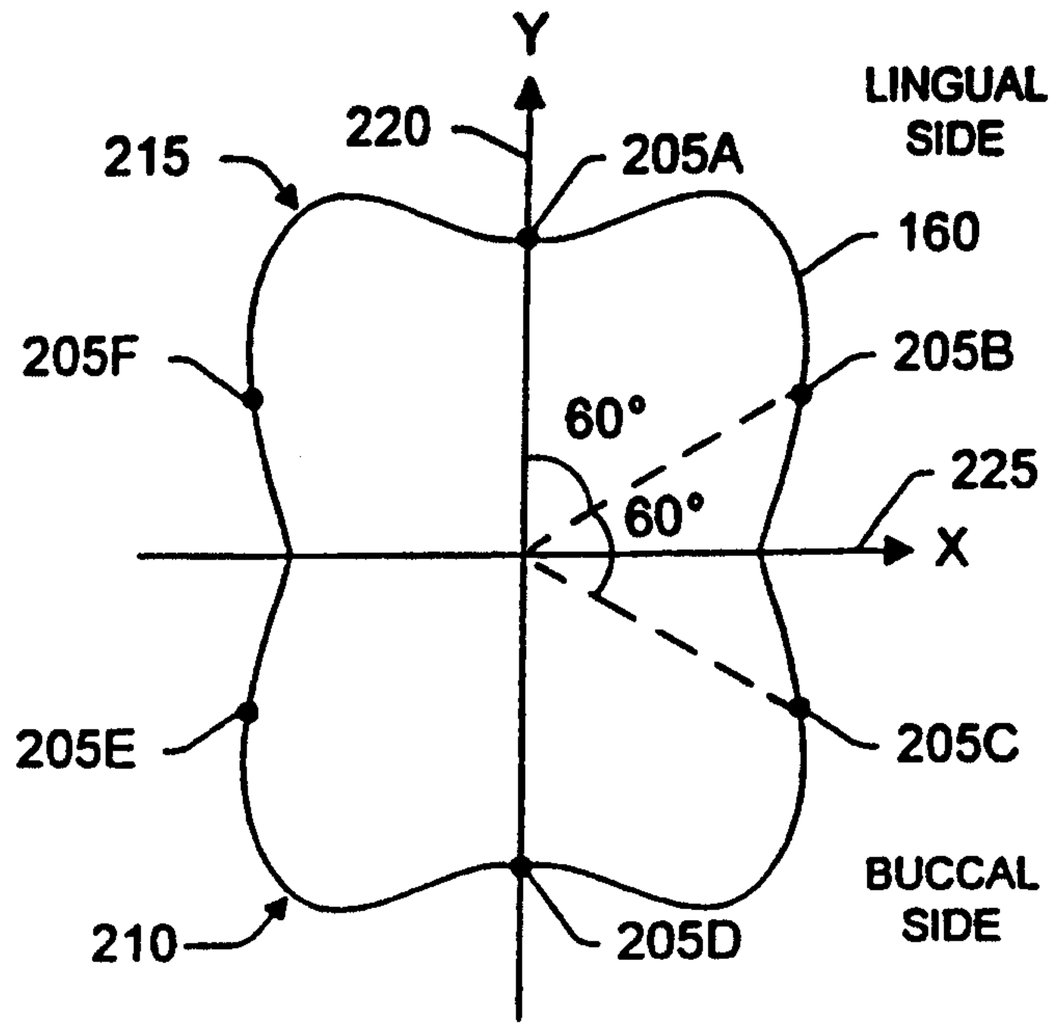

Y
LINGUAL SIDE
215
220
205A
160
205F
205B
60°
225
60°
X
205E
205C
BUCCAL SIDE
210
205D

FIG. 5

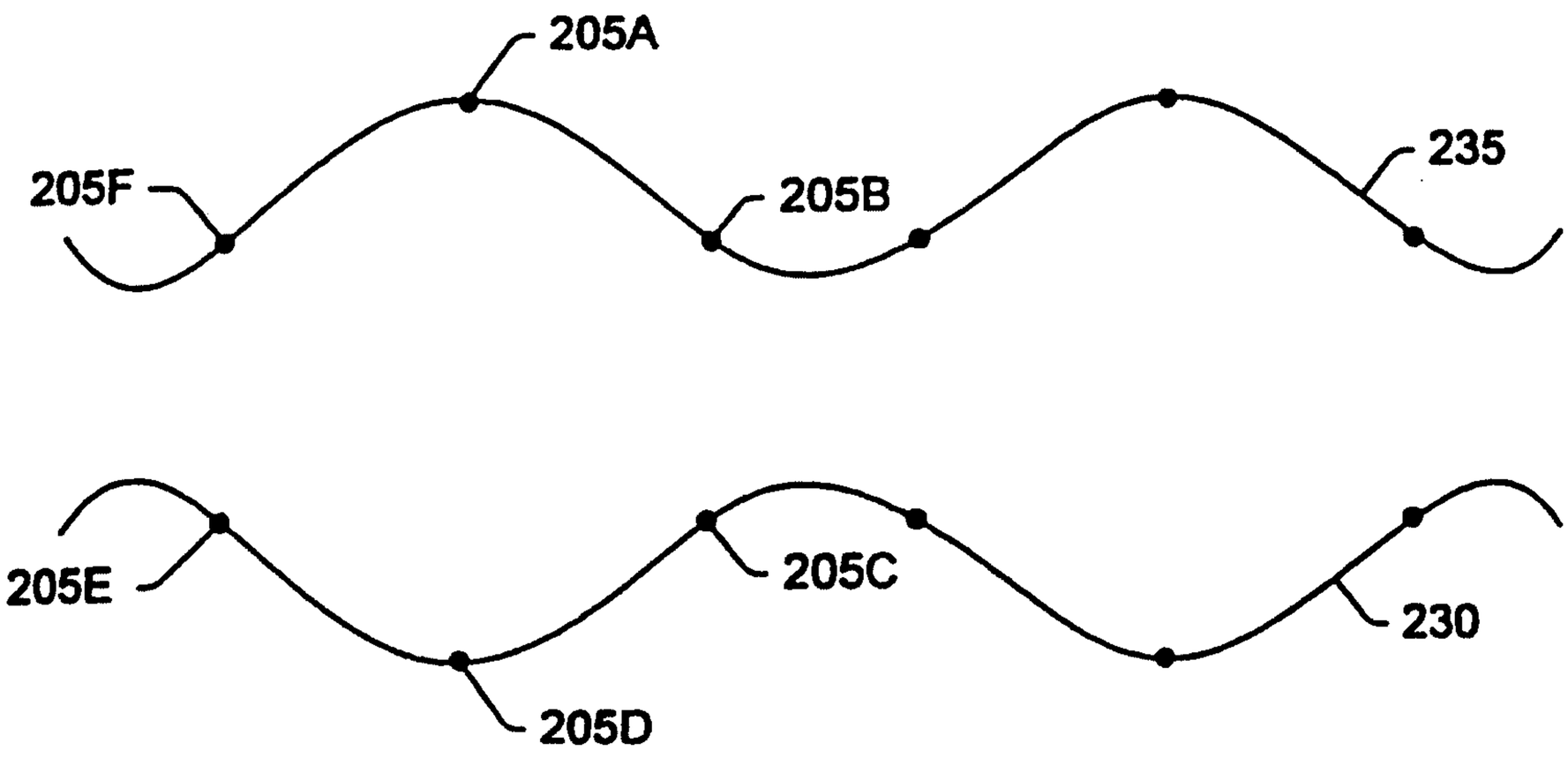

205A
205F
205B
235
205E
205C
230
205D

FIG. 6

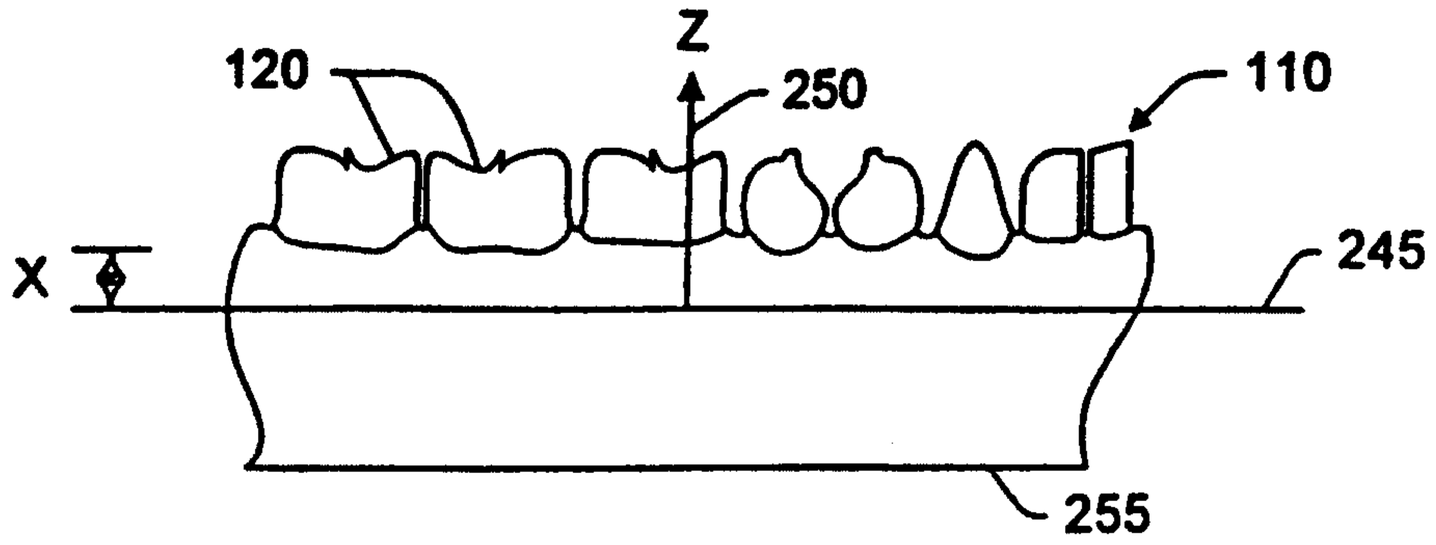


FIG. 7A

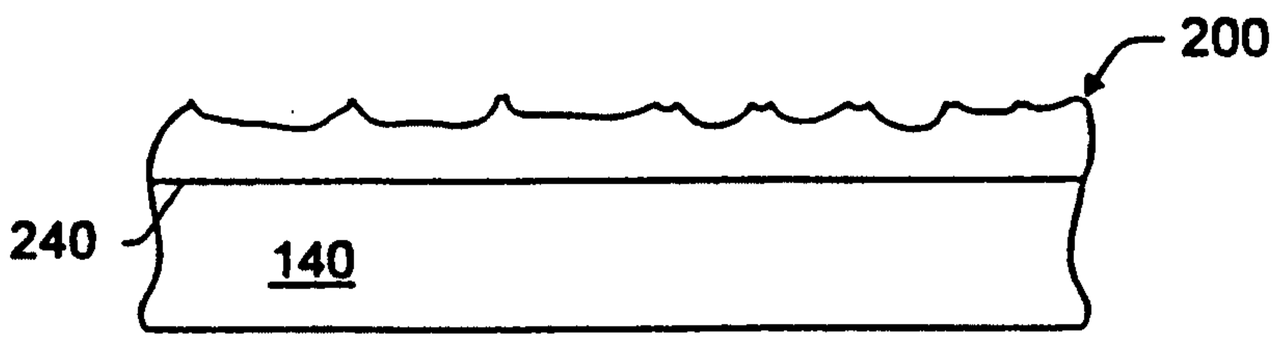


FIG. 7B

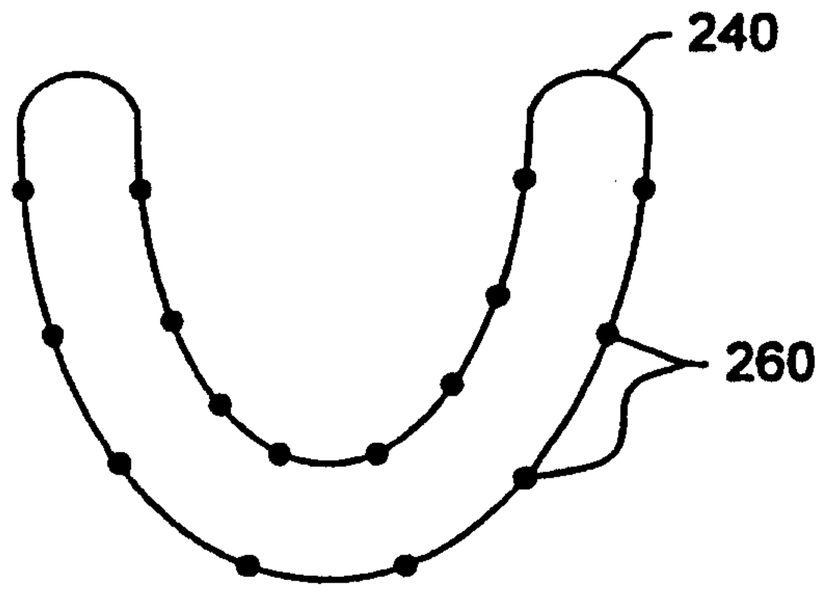


FIG. 7C

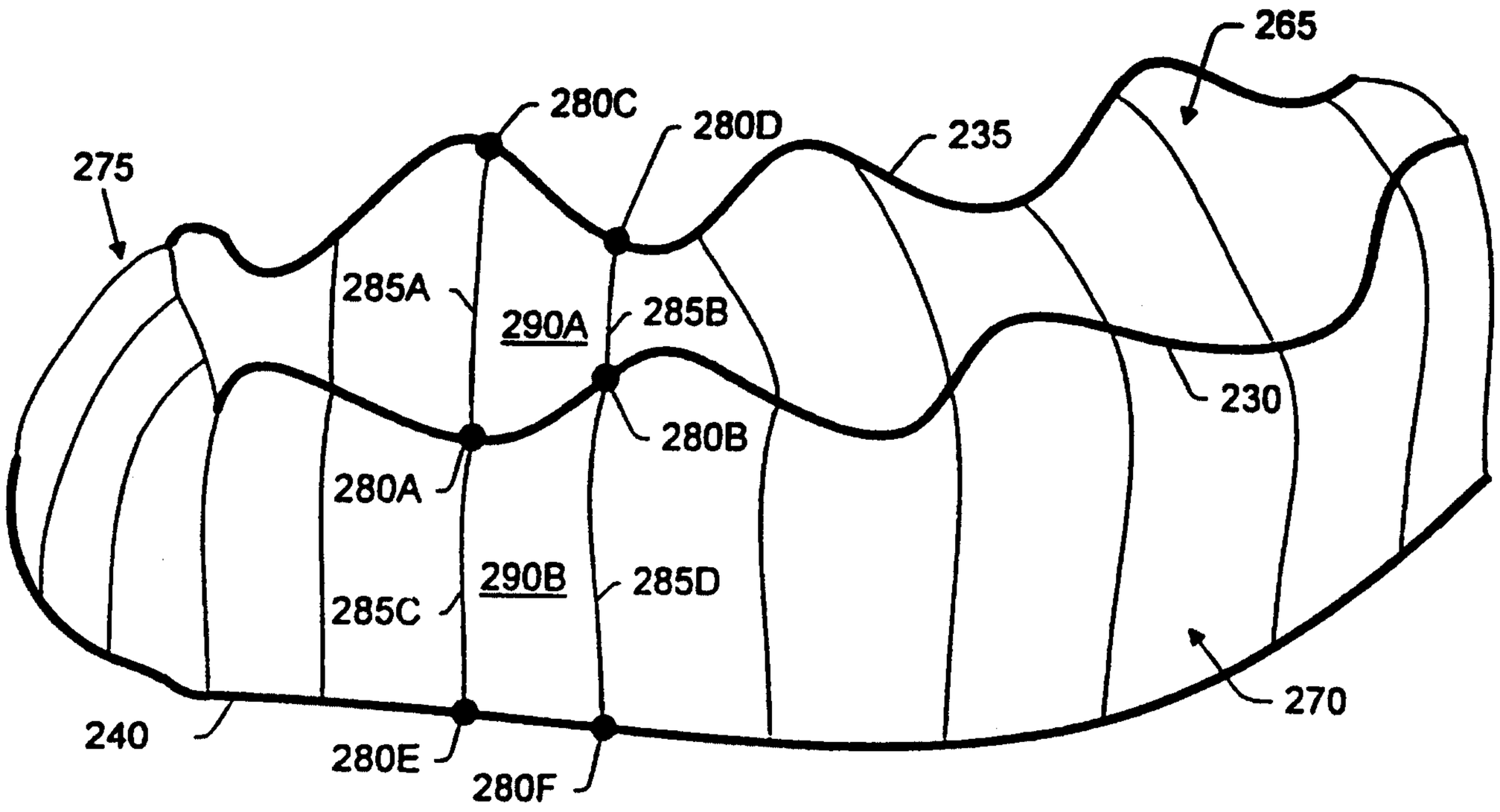


FIG. 8



FIG. 10

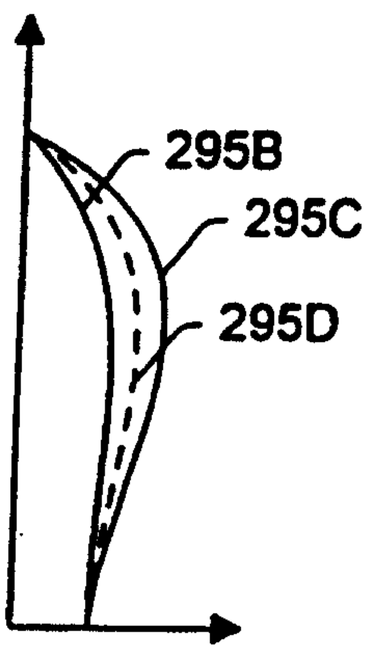


FIG. 11

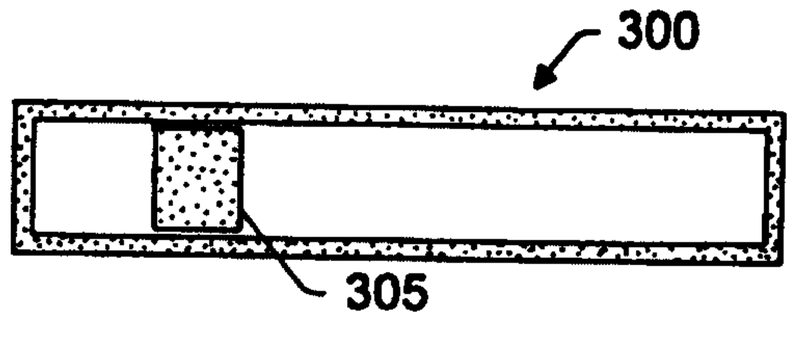


FIG. 13

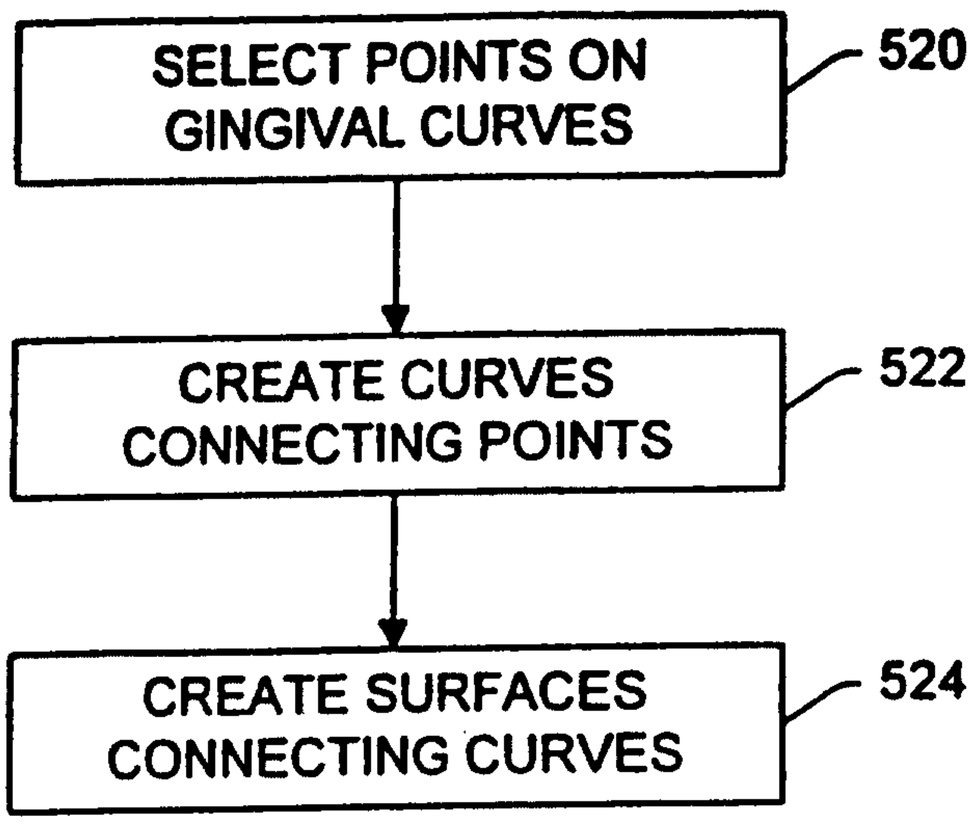

SELECT POINTS ON GINGIVAL CURVES
520
CREATE CURVES CONNECTING POINTS
522
CREATE SURFACES CONNECTING CURVES
524

FIG. 9

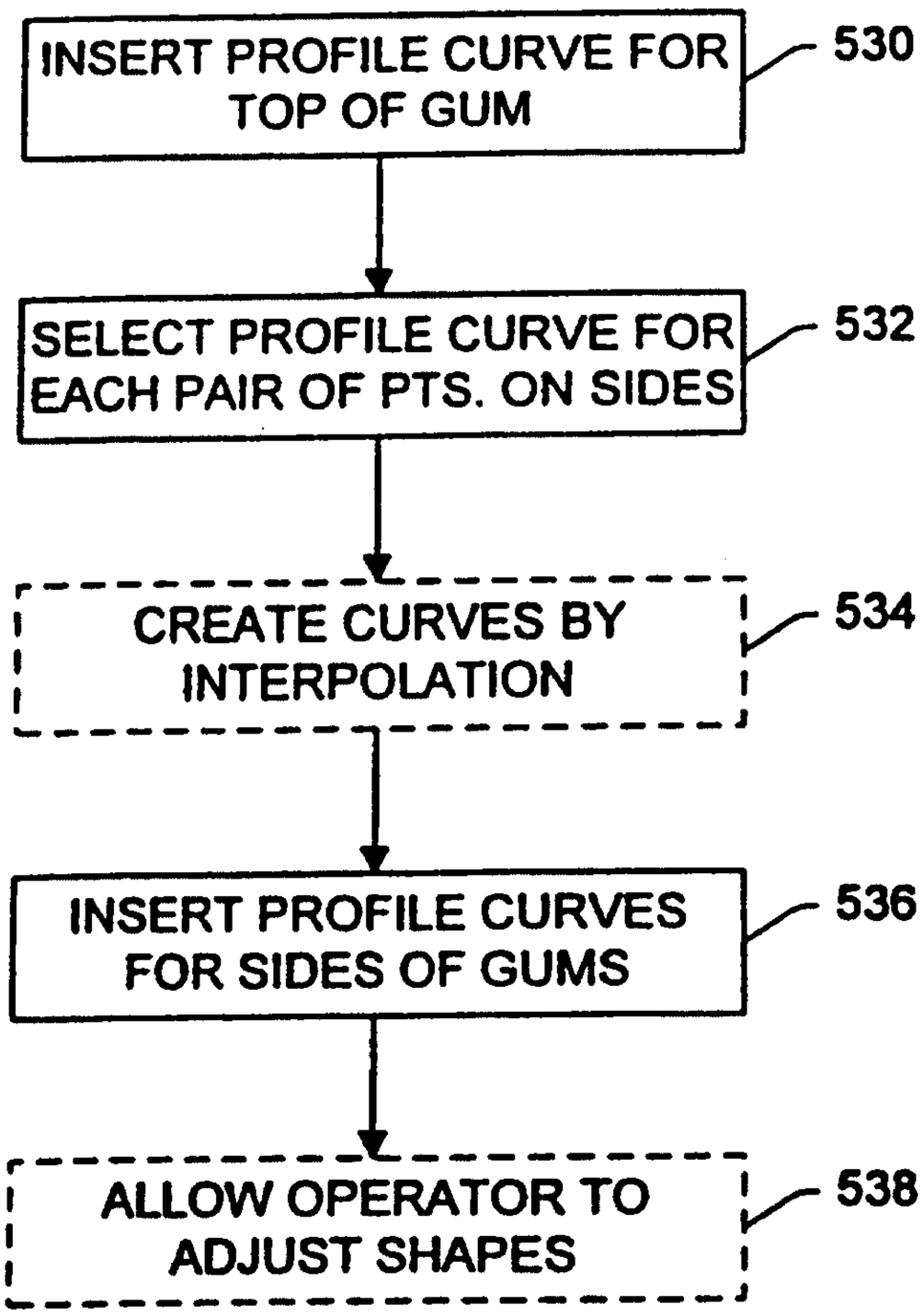

INSERT PROFILE CURVE FOR TOP OF GUM
530
SELECT PROFILE CURVE FOR EACH PAIR OF PTS. ON SIDES
532
CREATE CURVES BY INTERPOLATION
534
INSERT PROFILE CURVES FOR SIDES OF GUMS
536
ALLOW OPERATOR TO ADJUST SHAPES
538

FIG. 12

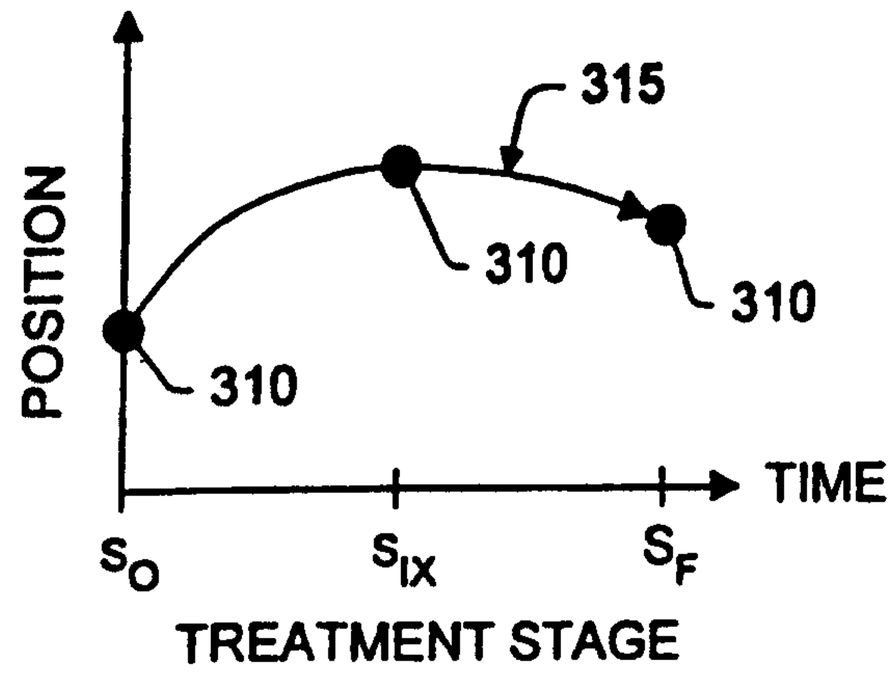


FIG. 14

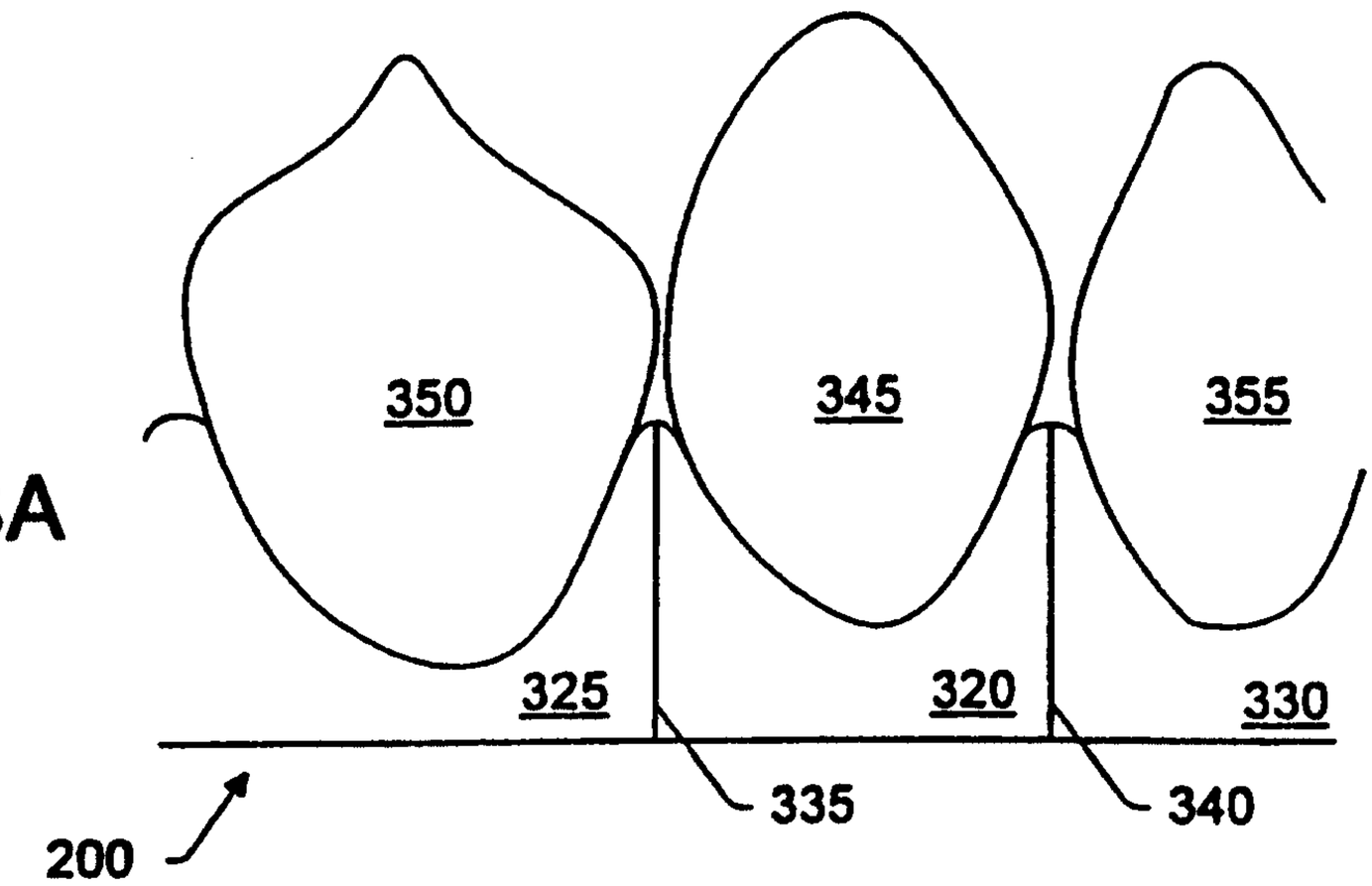


FIG. 18A

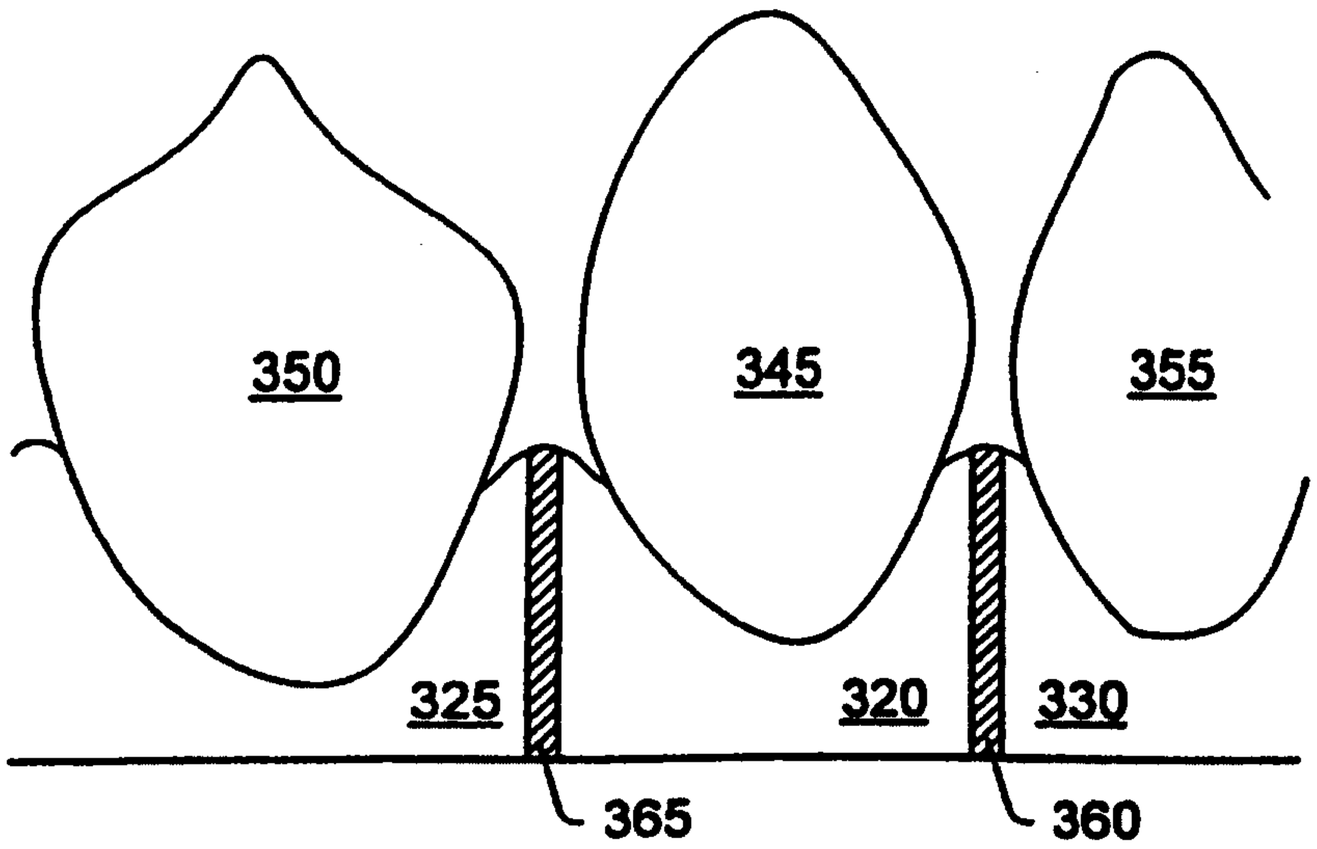


FIG. 18B

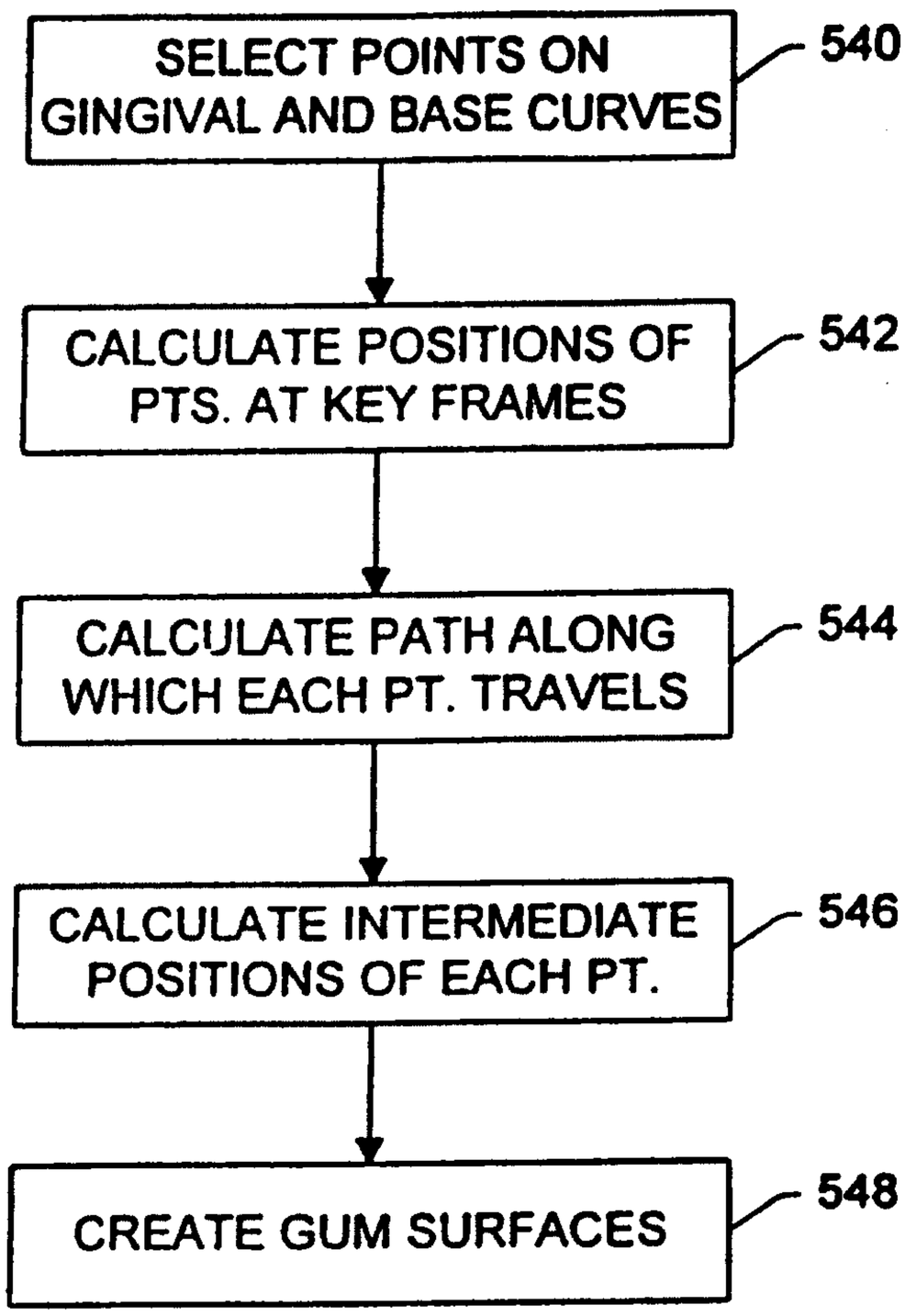

SELECT POINTS ON GINGIVAL AND BASE CURVES
540
CALCULATE POSITIONS OF PTS. AT KEY FRAMES
542
CALCULATE PATH ALONG WHICH EACH PT. TRAVELS
544
CALCULATE INTERMEDIATE POSITIONS OF EACH PT.
546
CREATE GUM SURFACES
548

FIG. 15

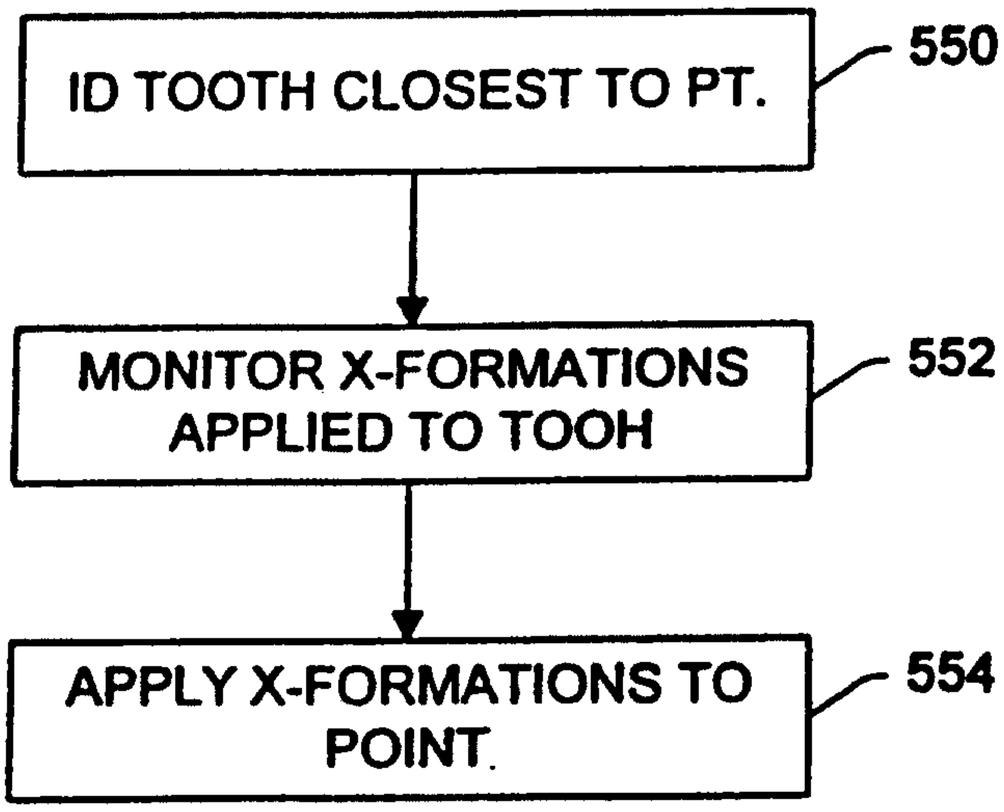

ID TOOTH CLOSEST TO PT.
550
MONITOR X-FORMATIONS APPLIED TO TOOH
552
APPLY X-FORMATIONS TO POINT.
554

FIG. 16

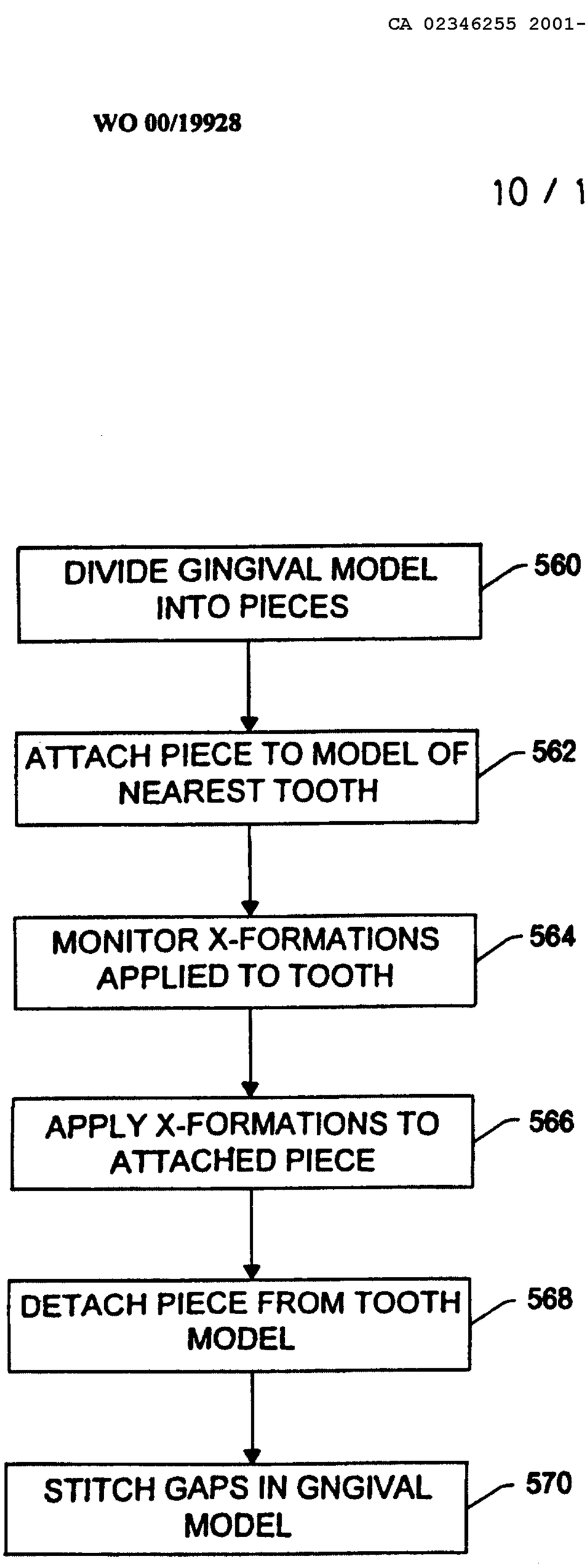

DIVIDE GINGIVAL MODEL INTO PIECES
560
ATTACH PIECE TO MODEL OF NEAREST TOOTH
562
MONITOR X-FORMATIONS APPLIED TO TOOTH
564
APPLY X-FORMATIONS TO ATTACHED PIECE
566
DETACH PIECE FROM TOOTH MODEL
568
STITCH GAPS IN GNGIVAL MODEL
570

FIG. 17

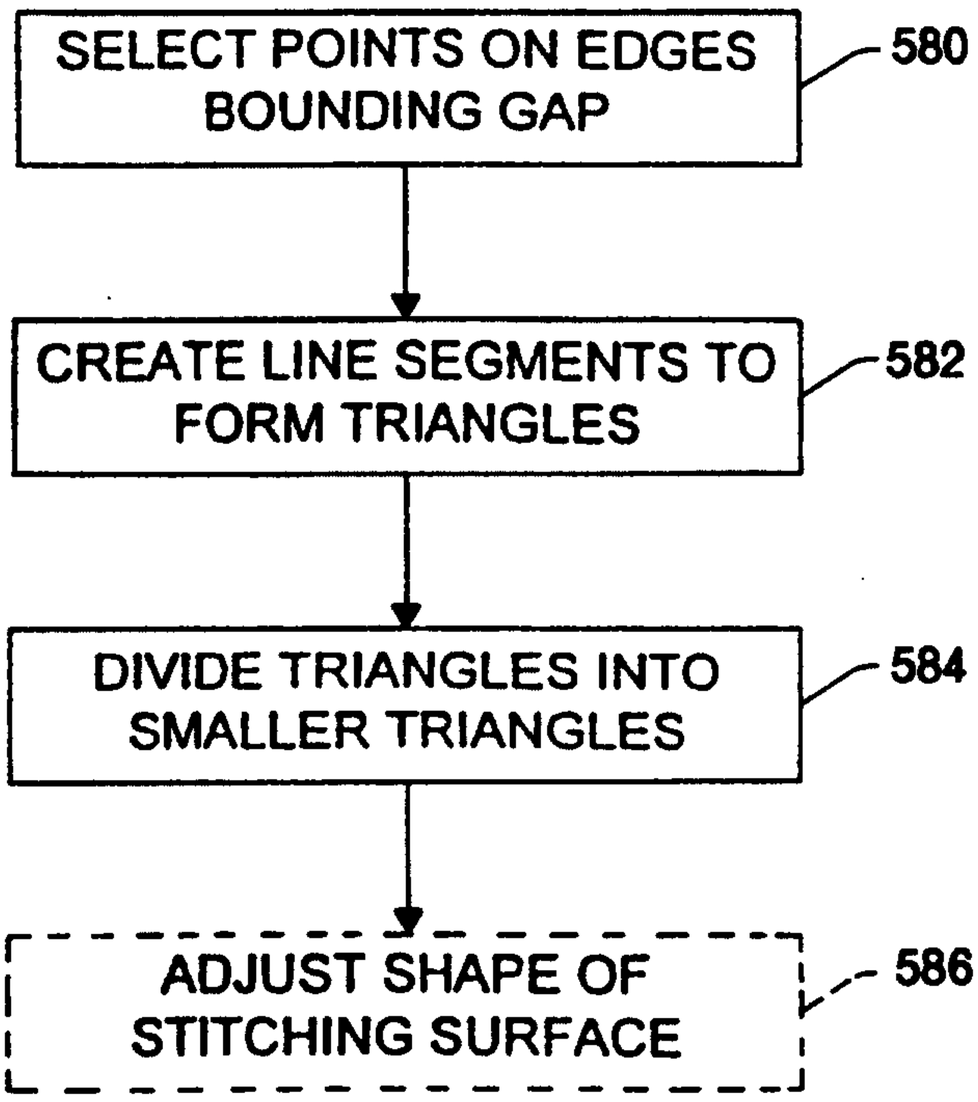

SELECT POINTS ON EDGES BOUNDING GAP
580
CREATE LINE SEGMENTS TO FORM TRIANGLES
582
DIVIDE TRIANGLES INTO SMALLER TRIANGLES
584
ADJUST SHAPE OF STITCHING SURFACE
586

FIG. 20

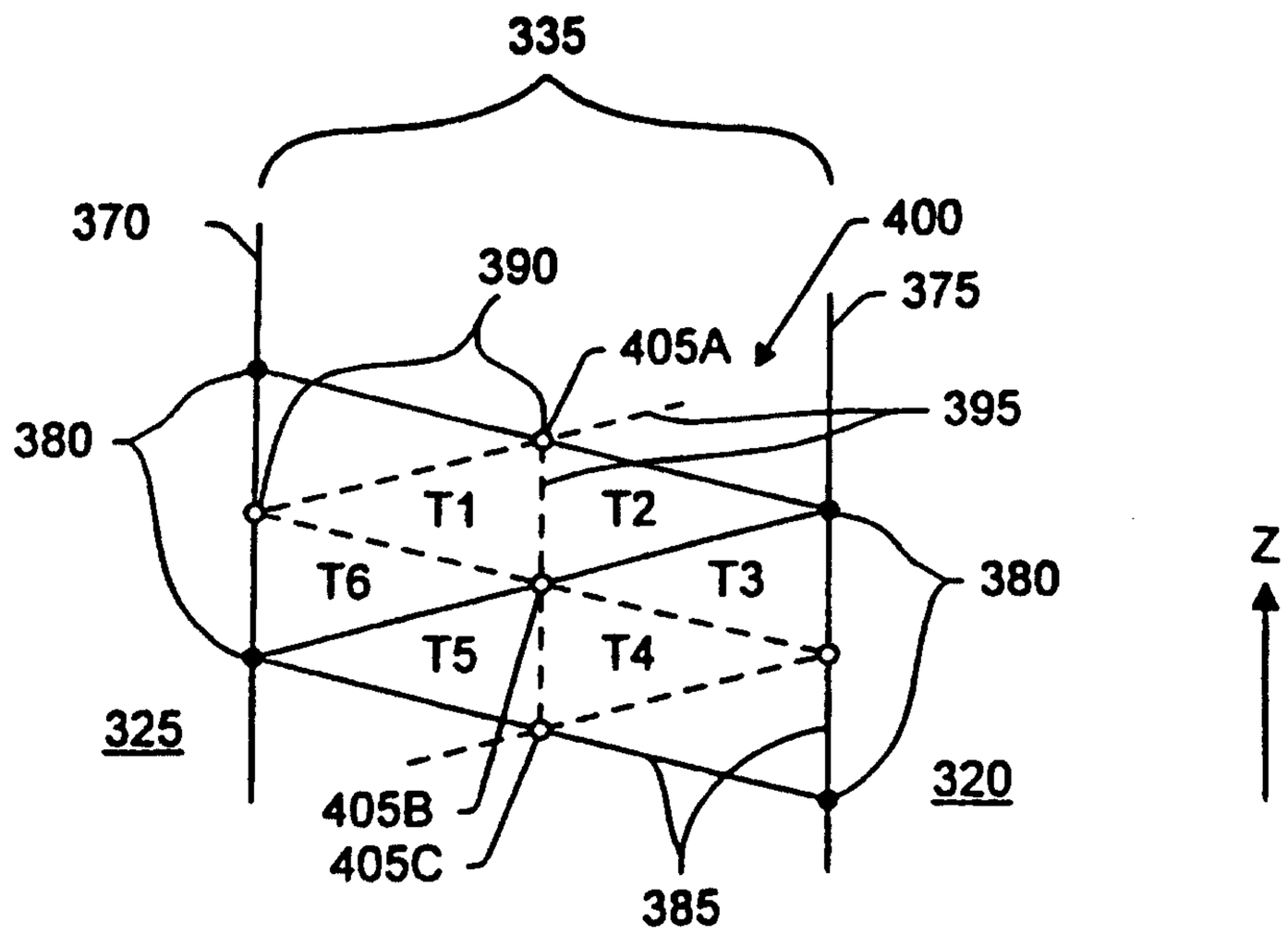

335
370
400
390
375
405A
380
395
T1
T2
T6
T3
380
T5
T4
325
320
405B
405C
385
Z

FIG. 19

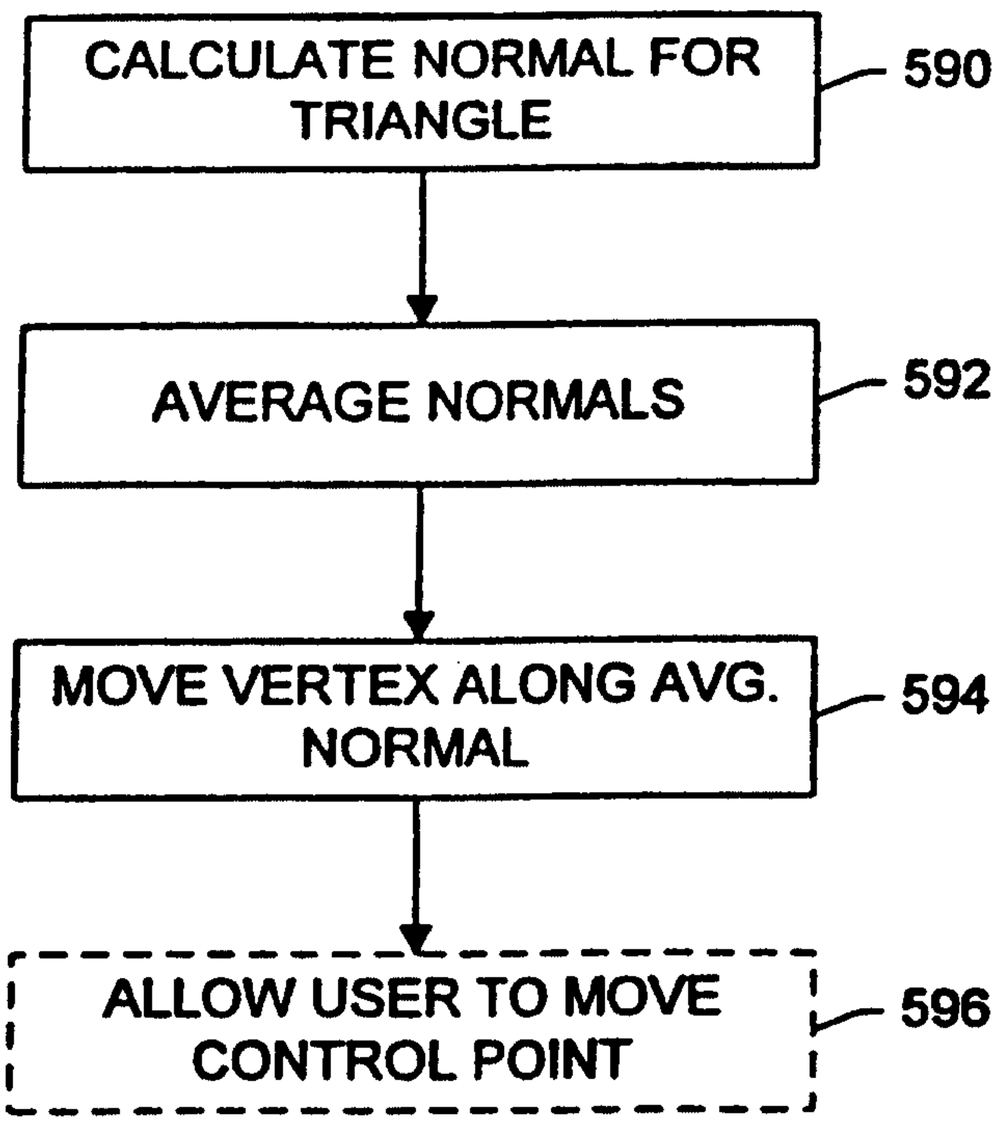
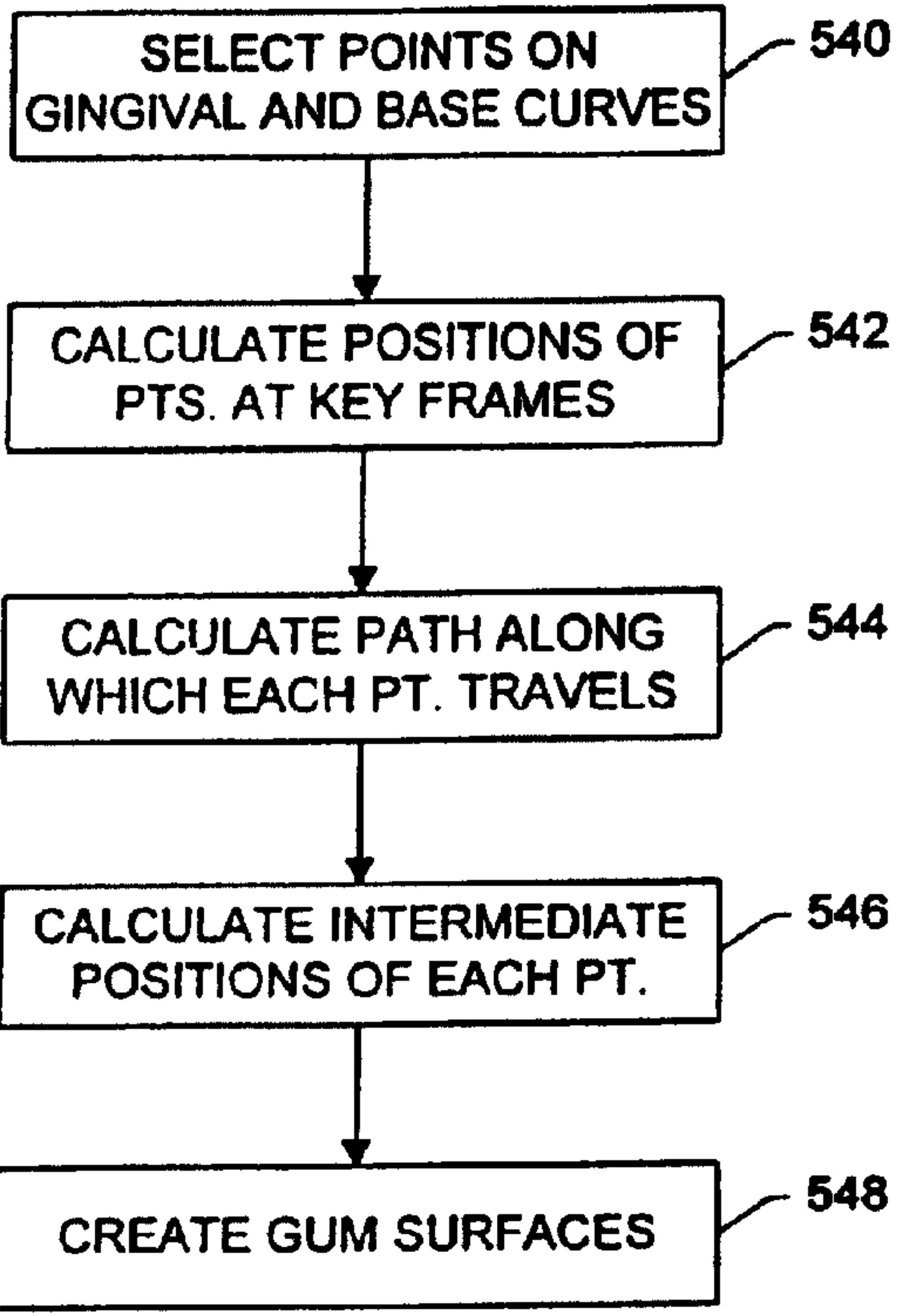

CALCULATE NORMAL FOR TRIANGLE
590
AVERAGE NORMALS
592
MOVE VERTEX ALONG AVG. NORMAL
594
ALLOW USER TO MOVE CONTROL POINT
596

FIG. 21


SELECT POINTS ON GINGIVAL AND BASE CURVES
540
CALCULATE POSITIONS OF PTS. AT KEY FRAMES
542
CALCULATE PATH ALONG WHICH EACH PT. TRAVELS
544
CALCULATE INTERMEDIATE POSITIONS OF EACH PT.
546
CREATE GUM SURFACES
548