

In search of anatomic truth: 3-dimensional digital modeling and the future of orthodontics

William E. Harrell, Jr, DMD,^a David C. Hatcher, DDS, MSc, MRCD(c),^b and Raymond L. Bolt, DMD^c

Alexander City, Ala, and Sacramento, Calif

The goal of imaging in medicine and dentistry has been to display a patient's *anatomic truth*.¹⁻³ Until now, imaging technology has been largely confined to 2 dimensions. Some 3-dimensional (3D) imaging techniques have been developed, but they are limited by the amount of information they can display and by their static nature. The development of an interactive 3D digital model of a patient's anatomy would greatly improve our ability to determine different treatment options, to monitor changes over time (the fourth dimension), to predict and display final treatment results, and to measure treatment outcomes more accurately.

2D AND 3D DIAGNOSIS AND TREATMENT PLANNING

In the 1930s, Broadbent⁴ used his original design of the cephalostat to analyze the craniofacial structures from standardized frontal and lateral radiographic images. Although the 2-dimensional (2D) images he studied did not represent the patient's 3D anatomic truth, they were still an attempt to understand the 3-dimensionality of the patient from two 90° views that were calibrated with an acetate overlay called "the orientator."

In the 1940s and 1950s, orthodontists began to rely on the lateral cephalometric radiograph as a diagnostic aid, and diagnostic ability was confined to 2 dimensions. Ricketts,⁵ understanding the importance of 3D anatomy, introduced the frontal cephalometric radiographic analysis to aid in diagnosis. Clinicians today routinely use additional 2D images, including pan-

oramic x-rays, facial and intraoral photographs, and cephalometric tracings. Even so, 2D views have limitations: geometric, rotational, and head positioning errors mean that the anatomy is not accurately represented; some elements can be obscured; and calibrating the views is a problem.

In the 1970s and 1980s, Baumrind⁶⁻⁸ pioneered a mechanical research solution to improve landmark identification in 3 dimensions. His interest and research in 3D imaging resulted in several landmark articles that have added much to the understanding of the 3D nature of patients. In Great Britain, Moss^{9,10} has performed a tremendous amount of work in the 3D reconstruction of the face and other body parts with 3D computed tomography and laser scanning techniques. In the United States, Grayson et al¹¹ helped lay the foundation on which to build an anatomically accurate 3D analysis.

Enlow¹² said:

Traditional cephalometrics was developed before there was a working understanding of the biologic processes of facial growth. Now, with the imminent advent of (1) very advanced computer 3-dimensional imaging and effective visualization, and (2) with our markedly advancing and really meaningful understanding of the biology of craniofacial development, the marriage of (1) and (2) is going to turn craniofacial diagnosis inside out within the foreseeable future. . . . The near-future will be based on the actual biology of an individual's own craniofacial growth and development, and it will be determined by a 3-dimensional evaluation based on that person's actual morphogenic characteristics, not simply developmentally irrelevant radiographic landmarks.

Even so, the only true 3D information routinely used today is plaster study models of the teeth, and the models are not accurately merged or calibrated with the other diagnostic information. Some techniques exist to create 3D digital study models that can be viewed on a computer screen. Although these might be accurate representations of the occlusal anatomy, they still have the limitation of showing only the crowns and occlusal surfaces of the teeth, and they cannot show the true size, location, or relationships of the roots of the teeth

^aPrivate practice, Alexander City, Ala; member of the AAO Council on Information Technology and the ADA Standards Committee on Dental Informatics.

^bOral and maxillofacial radiologist, Sacramento, Calif; acting associate professor, Department of Oral and Maxillofacial Surgery, University of California San Francisco.

^cPrivate practice, Alexander City, Ala.

The authors have a financial interest in Acuscape International, Inc.

Reprint requests to: William E. Harrell, Jr, DMD, Suite 1-A, Medical Arts Bldg, 125 Alison Dr, Alexander City, AL 35010; e-mail, weh@acuscape.com. Am J Orthod Dentofacial Orthop 2002;122:325-30

Copyright © 2002 by the American Association of Orthodontists.

0889-5406/2002/\$35.00 + 0 8/1/126147

doi:10.1067/mod.2002.126147

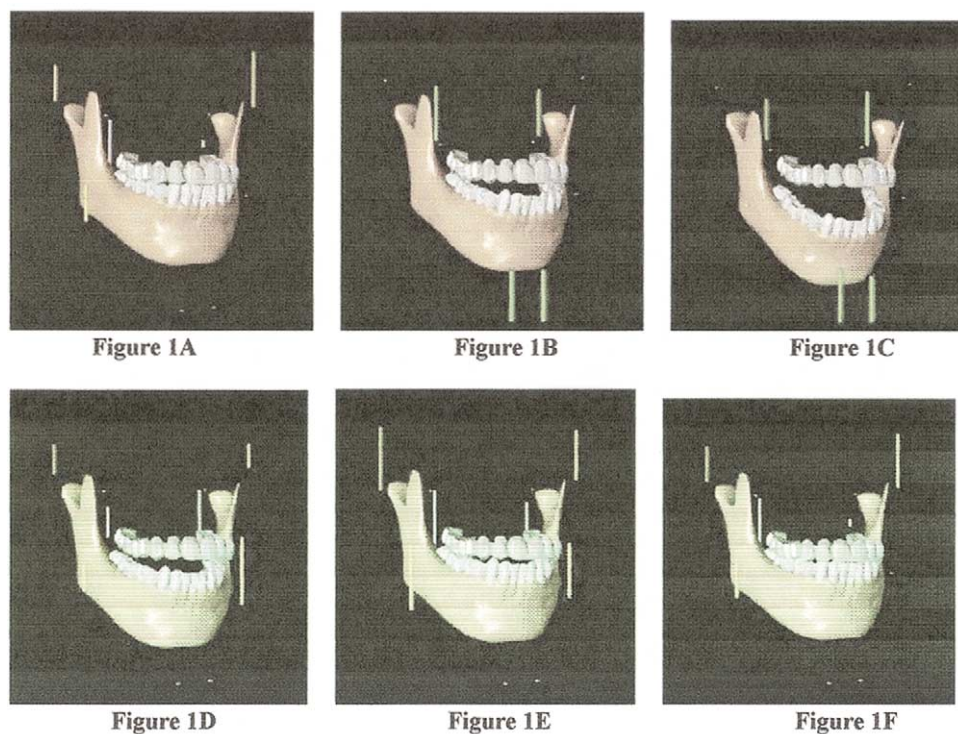


Fig 1. Screen captures of dynamic 3D model of opening and closing cycle by Hannam and Langenbach.¹³ Food bolus (not shown) between right first molars was 3 mm thick and required 60 N to compress. Molars made contact bilaterally. Actuators driving the cycle represented 18 jaw muscles, including locations, cross-sectional sizes, tendons, length-tension, velocity-tension curves, and activation profiles. (Reprinted with permission from Elsevier Science.)

and other anatomy. Various scanning techniques, including laser scans, structured light, destructive scans, computed tomography scans, magnetic resonance imaging, and ultrasound are now available for 3D reconstruction of anatomy. However, these techniques have not routinely provided practical solutions in orthodontics or oral surgery because they involve increased doses of radiation, significantly greater costs, or the need for massive computer processing of the data. Furthermore, the amount of volumetric data generated is not always practical or necessary in the routine practice of orthodontics, oral surgery, or dentistry.

DYNAMIC MODELING

Hannam and Langenbach,¹³ from the University of British Columbia, have developed 3D dynamic models that can be used to analyze the interaction between structure and function. Figure 1 shows their 3D model of an opening and closing cycle; the vertical bars represent muscle activity during the chewing stroke. (To see the model in action, go to www.acuscape.com/hannam2.html.) The models can be used to predict

muscular, occlusal, and articular biomechanical events during simulated function and to examine deviations in form and function.

A dynamic 3D model is different from the 3D data provided by computed tomography or other 3D methods because the anatomic parts, ie, the muscles, teeth, bone, and soft tissues, are separate and can be manipulated, moved, and changed individually, creating a true interactive, patient-specific simulation.

Dynamic, patient-specific 3D digital models that are routinely available would be a valuable aid to dentistry and medicine. An orthodontist, oral surgeon, or other dental specialist could use a computerized 3D replica of a patient's anatomy to make rapid and accurate diagnoses, determine treatment options, monitor changes over time, predict and display final treatment results, and more accurately measure treatment outcomes on the basis of a patient's actual morphogenic characteristics and an understanding of craniofacial growth and development. 3D models would also help the clinician to communicate with an interdisciplinary treatment team as well as patients and their parents.

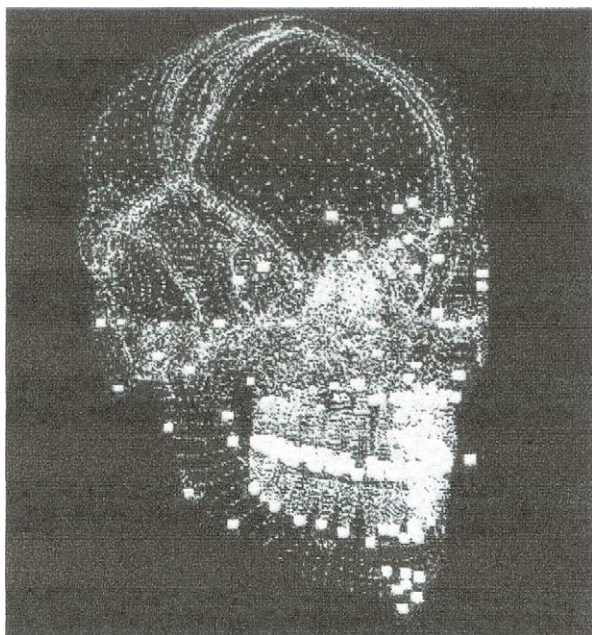


Fig 2. Acuscape dotPROfile matrix.

3D DIGITAL PATIENT—VIRTUAL PATIENT

Acuscape International, Inc (Glendora, Calif), has developed a method that combines standard cephalometric radiographs and routine photographs to create a 3D matrix, or a 3D digital patient. Working closely with Science Applications International Corp, Advanced Technology Group (Huntsville, Ala), Acuscape has begun to apply advanced image processing techniques and to fuse multiple image modalities on the basis of classified work performed for the Department of Defense for image recognition, manipulation, and archiving. These advanced technologies, when applied to orthodontics, orthognathic surgery, plastic and reconstructive surgery, facial recognition, forensics, and orthopedics, will allow computer-assisted identification of anatomy and anatomic landmarks and the manipulation of 3D files in a web-based environment.

The underlying structure of the 3D digital patient is called a dotPROfile (Fig 2). The dotPROfile is a dimensionally accurate digital model comprising discrete landmarks in 3D space that define the contour of a patient's anatomy. To create this patient-specific, interactive 3D model, a doctor would collect the necessary images of the patient and send them to an image processing facility via the internet. There, a technician would process the data, create a 3D model, and return it to the doctor via the internet.

The clinician would then be able to manipulate the model in a number of ways, ie, adding photograph

texturing, rotating views, isolating specific parts, and comparing different renderings (Fig 3).

The 3D digital patient model is different from a 3D image, simulation, computer graphic, or computer visualization in that the 3D patient model is interactive and dynamic. The digital patient's anatomy is tied to a powerful database that enables the doctor to ask questions and obtain patient-specific information. For example, by adding functional information, the 3D digital patient could be shown to chew. Practicing clinicians of the 21st century will be able to diagnose and provide treatment planning by using digital 3D interactive models that represent their patients 3 dimensionally.

ACUSCAPE UNIVERSAL ANATOMIC DATABASE

Acuscape is creating the Acuscape Universal Anatomic Database, which will grow with the data mined from every new patient, creating a knowledge base that can be used for treatment simulations, monitoring treatment over time, enhancing and updating the general orthodontic database of anatomic measurements, and clinical and academic research. The database can be grouped into archetype or class models representing anatomic averages or ideal anatomy and further grouped by age, race, and sex. The archetype models are compared with the patient-specific model to arrive at a mathematical measurement of difference between the two 3D models. The data derived from an electronic medical or orthodontic record can allow for data collection for clinical information and academic research as a by-product of routine clinical record keeping. This is an important aspect of a newly developing area called *orthodontic informatics*.

Orthodontic informatics, a new area of study, is a subdivision of dental informatics, which is a subdivision of medical informatics. Medical informatics is an established scientific area in medicine that deals with the storage, retrieval, sharing, and optimal use of biomedical information. Paraphrasing Shortliffe's definition of medical informatics,¹⁴ orthodontic informatics deals with the storage, retrieval, sharing, and optimal use of orthodontic, orthognathic, and dentofacial orthopedic information of the craniofacial region for decision making and problem solving (diagnosis and treatment planning). Also a subdiscipline of medical informatics is *imaging informatics*,¹⁴ which plays a significant role in orthodontics because we use imaging every day in our practices. Shortliffe¹⁴ describes the role of imaging in health care (imaging informatics) as "a central part of the assessment of response to treatment and estimation of prognosis. In addition, imaging plays important roles in medical communication and education, as well as research."

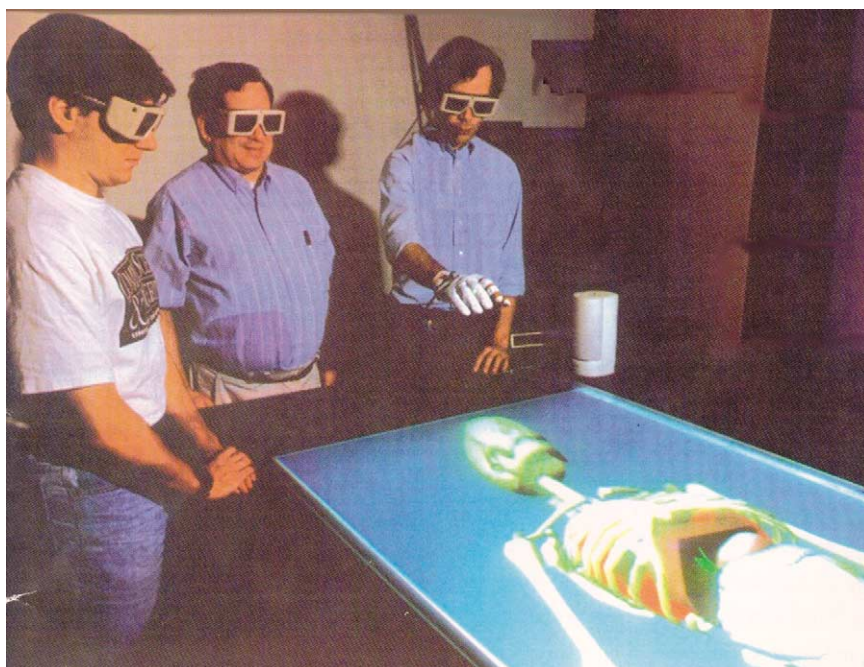


Fig 4. Medical application shown on virtual workbench. True visual depth information is gained from using stereoscopic glasses, giving binocular visualization to 3D model. Both gestures and speech recognition are used to interact with virtual patient. (Used with permission from Virtual Reality Laboratory, Naval Research Laboratory, Dr Lawrence Rosenblum, director.)

between hard and soft tissues (eg, tissue elastic properties, tissue hardness, and soft tissue's interaction with bone and tooth movement) to be expressed in the 3D digital patient model. This will equip the doctor with better tools to analyze the 3D anatomic truth of the patients. In the future, dynamic, patient-specific 3D modeling will become a valuable tool in many medical and dental applications.

Another application is 3D computer stereoscopic visualization with binocular vision, which uses either liquid-crystal shutter technology, colored lenses, or one of the "no glasses" technologies such as lenticular, autostereoscopic display, or the newer direct retinal display.¹⁶ This technology will give doctors of the future the ability not only to visualize in 3D but also to visualize depth information with binocular vision, or stereopsis.¹⁷⁻¹⁹ This normal, "real-world" viewing improves the qualitative aspects of visualization and greatly improves quantitative visual analysis.²⁰ 3D stereoscopic viewing will also lead to the ability to add prehension (reach and grasp)²¹⁻²³ and the haptic sense (touch)²⁴ to these 3D models with data gloves and virtual tools. A virtual workbench mode of viewing the patient's anatomy might become a standard consultation room tool for orthodontic offices of the future (Fig 4).²⁵

CONCLUSIONS

The development of a 3D virtual patient has many advantages:

- 3D spatial information without increased doses of radiation and significantly increased costs
- Access to a dynamic anatomic database and knowledge base
- Improved clinical and research outcomes
- Ability to share images and 3D models through the internet with other doctors and patients
- Treatment planning and 3D simulation on the basis of the patient's 3D morphologic anatomy
- Accurate 3D visualization with binocular vision for qualitative and quantitative analysis
- Virtual reality capabilities to enhance visual depth information
- The ability to interact with individual anatomic parts (ie, facial soft tissue, muscles, bone, and teeth) and to analyze their 3D spatial relationships

REFERENCES

1. Hatcher D. Maxillofacial imaging. In: McNeill C, editor. Science and practice of occlusion. Carol Stream [Ill]: Quintessence; 1997. p. 349-64.
2. Hatcher D. Diagnostic imaging. In: Davis H, Fonseca R, editors.

- Reconstruction preprosthetic oral and maxillofacial surgery. Philadelphia: W. B. Saunders; 1995. p. 86-123.
3. Quintero JC, Trosien A, Hatcher D, Kapila S. Craniofacial imaging in orthodontics: historical perspective, current status and future developments. *Angle Orthod* 1999; 69:491-506.
 4. Broadbent BH. A new x-ray technique and its applications to orthodontia. *Angle Orthod* 1931;1:45-66.
 5. Ricketts RM. Cephalometric analysis and synthesis. *Angle Orthod* 1961;31:141-56.
 6. Baumrind S. Mapping the skull in 3D. *J Calif Dent Assoc* 1972;48:22-31.
 7. Baumrind S, Moffitt FH, Curry S. Three-dimensional x-ray stereometry from paired coplanar images: a progress report. *Am J Orthod* 1983;84:292-312.
 8. Baumrind S, Moffitt FH, Curry S. The geometry of three-dimensional measurement from paired coplanar x-ray images. *Am J Orthod* 1983;84:313-22.
 9. Moss JP, Linney AD, Lowery MN. The use of three-dimensional techniques in facial esthetics. *Semin Orthod* 1995; 1:94-104.
 10. Moss JP. 2D or not 2D? That is the question. *Am J Orthod Dentofacial Orthop* 2000;117:580-1.
 11. Grayson B, Cutting C, Bookstein FL, Kim H, McCarthy JG. The three-dimensional cephalogram: theory, technique, and clinical application. *Am J Orthod Dentofacial Orthop* 1988;94:327-37.
 12. Enlow D. Discussion. *Am J Orthod Dentofacial Orthop* 2000;117:147.
 13. Langenbach GEJ, Hannam AG. The role of passive muscle tensions in a three-dimensional dynamic model of the human jaw. *Arch Oral Biol* 1999;44:557-73.
 14. Shortliffe EH, Perreault LE, Wiederhold G, Fagan LM. Medical informatics: computer applications in health care and biomedicine. 2nd ed. New York: Springer-Verlag; 2000.
 15. Redmond R. Wireless orthodontics. *Am J Orthod Dentofacial Orthop* 2001;120:325-7.
 16. Lipton L. Foundations of the stereoscopic cinema—a study in depth. New York: Van Nostrand Reinhold Co; 1982.
 17. Yeh Y, Silverman L. Spatial judgments with monoscopic and stereoscopic presentation of perspective displays. *Hum Factors* 1992;34:583-600.
 18. Kumar T, Glaser D. Shape analysis and stereopsis for human depth perception. *Vision Res* 1992;32:499-512.
 19. Van den Berg AV, Brenner E. Why two eyes are better than one for judgment headings. *Nature* 1999;371:700-2.
 20. Bishop P. Size constancy, depth constancy and vertical disparities: a further quantitative interpretation. *Biol Cybern* 1994;71:37-47.
 21. Servos P, Goodale M, Jakobson L. The role of binocular vision in prehension: a kinematic analysis. *Vision Res* 1992;32:1513-21.
 22. Servos P, Goodale M. Binocular vision and the on-line control of human prehension. *Exp Brain Res* 1994;98:119-27.
 23. Goodale M, Meenan JP, Bulthoff HH, Nicolle DA, Murphy KJ, Racicot CI. Separate neural pathways for visual analysis of object shape in perception and prehension. *Curr Biol* 1994;4: 604-10.
 24. Carts-Powell Y. Lab studies human, machine, and computer touch. SPIE International Society of Optical Engineering (<http://www.spie.org/web/oeer/june/jun99/touch.html>) OE Reports. Technology and Trends for the International Engineering Community, June 1999; No.186, p. 6.
 25. Carlson B. 3-D visualization and virtual reality in medical apps—now. *Advanced Imaging* 1996;11:36-8, 69.