sciendo

DOI: 10.2478/aoj-2007-0010

Three-dimensional computed craniofacial tomography (3D-CT): potential uses and limitations

Hong Jin Chan,* Michael Woods† and Damien Stella+

Private practice, Melbourne,* School of Dental Science, The University of Melbourne† and Department of Radiology, Royal Melbourne Hospital,+ Melbourne, Australia

Aims: To determine the potential uses and limitations of 3D-CT craniofacial imaging in contemporary clinical practice.
Methods: The relevant historical and contemporary literature was reviewed.
Results: There would seem to be many potential uses for 3D-CT craniofacial imaging in clinical practice. Significant limitations may, however, relate to the availability and cost of such imaging and the delivered radiation dose.
Conclusions: With continued research and development, the use of such 3D-CT craniofacial imaging techniques may become appropriate for future orthodontic and clinical diagnostic applications.
(Aust Orthod J 2007; 23: 55–64)

Received for publication: November 2006
Accepted: March 2007

Introduction

Broadbent[1] first introduced the use of cephalometry in dentistry approximately 36 years after the discovery of X-rays by Roentgen in 1895.[2] Despite accepted limitations, lateral and posteroanterior cephalometry is still considered to be a practical, affordable and low radiation dose imaging technique. To the trained eye, the information gained from these cephalograms is often adequate for use in clinical orthodontics. Despite the availability of perhaps more sophisticated imaging techniques, the replacement of cephalometry in orthodontic practice would require a real analysis of the cost:benefit ratio for individual orthodontic patients.

In 1917, Radon demonstrated that an infinite set of two-dimensional (2D) projections could be used to create a representative image of a three-dimensional (3D) structure. Hounsfield later developed the computerised axial transverse scanning technique and the first commercially available computed tomography (CT) scanner was later marketed in 1972.[3] By the early 1980s, both researchers and clinicians were investigating the potential for 3D imaging of craniofacial structures and deformities. Continued development of CT scanners since then, has involved changes in the geometry of the radiation beam, the number of detector rows, the image resolution and the speed and efficiency of image acquisition.

3D reconstructed images may enhance the clinician's three-dimensional perception of anatomical and morphological features of individual patients, in turn, facilitating the development of a more appropriate individualised treatment plan than might have been possible with the use of conventional 2D imaging techniques. With all this in mind, this review article addresses the basic principles behind the use of CT imaging, the potential clinical applications of 3D-CT images in orthodontic practice and the possible limitations of the technique.

What is computed tomography?

The basic component of a helical CT scanner is the gantry that continuously rotates during volume data acquisition, as the patient is transported through the machine.

The gantry is comprised of numerous rows of detector arrays, an X-ray source and the patient

support couch.[4] The desired collimation of X-ray photons is directed at the patient and subsequently received by the detector array rows. The volume coverage performance of a CT scanner is limited by its maximum pitch. Pitch is defined as the rate of table travel per gantry rotation, divided by the beam collimation or slice thickness.[4,5] An increase in table travel speed, pitch or collimation in turn increases volume coverage speed. The image resolution is, however, inversely affected by an increasing table travel speed or collimation.[4,5]

The more current multidetector row CT (MDCT) scanners permit acquisition of volume data up to 64 contiguous slices with each gantry rotation. While the reconstructed slice thickness cannot be smaller than the effective detector row thickness,[3,6] 64-slice CT results in significant improvement in diagnostic accuracy as a result of increased spatial and temporal resolution[7,8] compared with the earlier 4- or 16-slice MDCT systems.

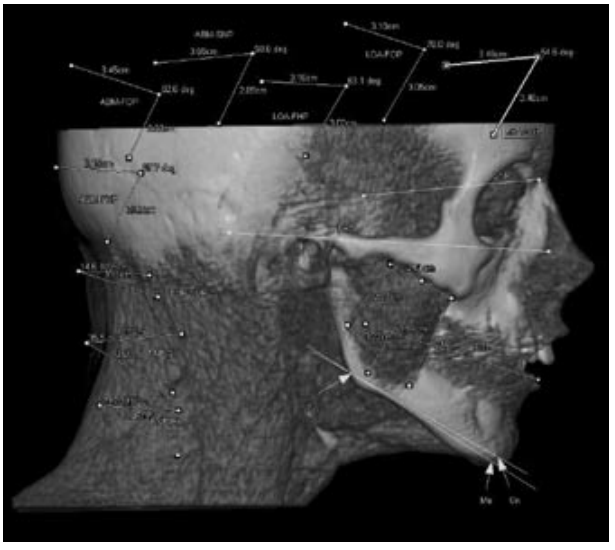


Figure 1. An example of a volume-rendering 3D lateral profile image with selective illustration of the superficial masseter, temporalis and neck muscles. Computed analyses also help to highlight the individual underlying vertical facial pattern.

Three-dimensional reconstruction from computed tomography images

3D imaging is not new. It has, however, evolved rapidly over the past 20 years and has found applications in both medicine and dentistry. Uses for 3D imaging in orthodontics and oral and maxillofacial surgery may include pre- and post-orthodontic assessment of dentoskeletal relationships and facial aesthetics, evaluation of orthodontic outcomes with regard to the effects on both hard and soft tissues, 3D treatment planning and simulation, 3D fabrication of customised orthodontic archwires and computerised archiving of 3D records.[9]

The greater understanding of mathematical algorithms has underpinned the rapid development of 3D-CT rendering techniques. The degree of resolution and the accuracy of 3D-CT images are both continually improving, with the use of smaller axial CT slice thickness and slice overlapping scans. Cavalcanti et al.[10] found a high level of precision and accuracy in their study of anthropometric measurements of both soft and hard tissues using 3D-CT images. Similar studies by Matteson et al.[11] and Hildebolt et al.[12] on measurements of the skull using 3D-CT images have also shown favourable results. The typical image matrix for most CT scanners is 512 × 512 pixels. Pixels are 2D entities and therefore, voxels provide a better representation of the tissue volume. Voxels can be thought of as tiny cubes arranged adjacent to each other. Each voxel can be calculated by multiplying pixel dimensions by the slice width,[3] thereby representing the density of the particular anatomical structure.[13] Based on the original series of CT data, new 2D or 3D axial or correspondent multiplanar reconstructed (MPR) images can then be created and further manipulated for improved visualisation. These MPR images can be used to display CT slices in any direction[14] and have been validated for quantitative and qualitative analyses.[10]

Different types of tissues are characterised by a specific range of voxel values, often defined in Hounsfield units (HU). In order to visualise separate anatomical structures, such as bone, teeth, muscles or skin, a relationship between voxel value and voxel opacity value must first be established. This is referred to as the transfer function.[13] This transfer function can also match voxel values to colours. The combined use of colours, threshold HU and opacity values preselected for a range of voxel values, helps to differentiate the volumetric data and hence the selective display of the anatomical structures of interest (Figure 1).[13–15] Contemporary volume rendering 3D images can therefore demonstrate specific internal features of a 3D structure based on this concept.

Figure 2. Analysis of the cross-sectional areas of the masseter, medial pterygoid and lateral pterygoid muscles. Transfer functions and a predetermined range of window level and width were applied to selectively block out unwanted overlying fatty and skin structures.

Other applications of 3D-CT imaging techniques may include shaded surface display (SSD), maximum intensity projection (MIP), model production and virtual reality. Shaded surface display assesses the surface details of specific structures e.g. bone, teeth or skin, in three-dimensions.[14] Projection, hidden-part removal and shading are all applied in this viewing mode, to impart a sense of 3D perspective to the created image.[16] MIP, on the other hand, is used more often in medicine to enhance angiographic images.

Potential uses of 3D-CT images in clinical orthodontics

With the development of helical MDCT scanners and sophisticated 3D rendering software, 3D-CT images can now be more readily generated and potentially used for both diagnostic imaging and biomedical research in dentistry.[14] Previous researchers have actually assessed the practicality of utilising such 3D-CT scans in the clinical evaluation of the masseter muscle morphology and the anthropometric measurements of the craniofacial region.[10,17–19] Katsumata et al.[19] and Ariji et al.,[17] for instance, evaluated the surface topography of the masseter muscle, and its cross-sectional area and orientation to the Frankfort horizontal plane in adults presenting with mandibular prognathism. Similarly, Kitai et al.,[18] investigated the morphological association of craniofacial form within a similar sample group with the cross-sectional areas and volumes of the temporal and masseter muscles, respectively.

Following these investigations, a recent 3D-CT study was undertaken to assess the cross-sectional area, the volume and the spatial orientation of the masseter, medial pterygoid and lateral pterygoid muscles in young orthodontic patients presenting with different

Figure 3. Calculations of muscular volumes based on composites of all muscular outlines which had been digitally traced from the sequential axial CT images.

underlying vertical facial patterns (Figures 2 and 3).[20] Based on the results of that study, craniofacial form, and the cross-sectional area and volume of these muscles could be accurately measured using 3D-CT images with a high level of reproducibility. The surface topography of the superficial masseter could also be identified and measured (Figure 1).

3D-CT images are capable of providing an accurate representation of the osseous structures of the craniofacial region. The ability to regenerate and manipulate these images enhances the accuracy of the analytical measurements typically used with traditional 2D cephalograms. The inherent errors associated with plain radiograph cephalometry can therefore be eliminated. Such errors would include those of radiographic magnification and poor head posturing during exposure, as well as examiner-biased assumptions in locating anatomical landmarks for structures that are either displaced or not clearly seen. 3D-CT cephalometry is a potentially powerful craniofacial measurement tool and has proven to be highly accurate and reliable.[21]

Also, with the application of transfer functions during 3D-CT volume rendering techniques, an accurate perception of the 3D positions and angulations of the teeth is possible. This may include the 3D assessment of stages of the tooth development and eruption process, the relationship of underlying supernumerary teeth and impacted teeth to adjacent dental structures, the relationships between the tooth roots and the surrounding alveolar bone, and the location of the mandibular canal (Figure 4). Macchi et al.[22] described the combined use of CT technology and laser scanning of dental casts in the creation of an interactive 3D digital replica of the dental anatomy of an individual. From this, the 3D anatomical relationships between the teeth and with the surrounding bone can be viewed and altered according

Figure 4. Assessment of tooth position, angulations and relationships (including supernumerary and unerupted teeth) under the radiographic viewing mode.

to the effects of certain treatment goals prior to active treatment (e.g. for extractions, root torque changes).

The benefits of 3D simulated surgical planning with CT data have also been assessed.[23–25] The 3D visualisation of the facial skeleton, landmark identification, quantitative analysis of craniofacial structures, simulation of CT model osteotomies and surgical repositioning of bones, detection of skeletal interferences and superimposition of scans are among some of the reported benefits.[23,26,27] These features provide the opportunity for accurate evaluation and prediction of the outcomes of proposed craniomaxillofacial surgery in three-dimensions. This might not have been possible with the use of standard 2D diagnostic tools.[23] A similar degree of accuracy and reliability in 3D-CT imaging for dental implant planning and placement has also been reported.[28,29] Following the precise planning of implant positions using interactive 3D-CT based software, customised guide splints and final dental prostheses are fabricated for delivery at the time of implant placement, ensuring high precision transfer of the planned positions to the operative field and an immediate rigid splinting of the installed implants.[30,31]

3D-CT technology can also be used to assess patients with congenital facial anomalies, asymmetries[26,32] and facial injuries.[15,33] The morphology and position of the temporomandibular joint (TMJ)[34] and the patency of the airway[35,36] can be similarly assessed (Figure 5). Kawamata et al.[35] and Fairburn et al.[36] have both described morphological changes in the airway of adult patients following orthognathic surgery. With regard to the TMJ region, MDCT images can provide an accurate assessment of condylar displacement and superior delineation of TMJ osseous changes and morphology.[37] However, magnetic resonance imaging (MRI) may still be a better alternative in the evaluation of the soft tissue changes and the internal derangement of the joint.[37–39] Nevertheless, considerable diagnostic possibilities exist with the use of multiplanar reconstructions of 3D-CT images from a single set of CT volume data. This may in the future be of great benefit for those managing complicated orthodontic cases.[40]

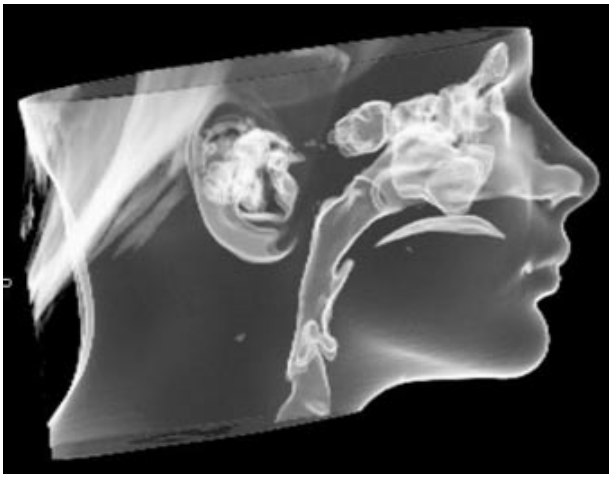


Figure 5. Semi-transparent 3D-CT image showing the outlines of the pharyngeal airway from the lateral view. The 1:1 ratio with the actual size can allow for volumetric measurement of the pharyngeal airway.

Limitations of the 3D-CT imaging technique

Radiation dose

Considerations that are unique to the paediatric population over their lifetime with repeated CT examinations may include increased radiosensitivity of certain tissues, a longer lifetime for radiation-related cancer to manifest, and a cumulative cancer risk for certain organs. However, great debate still exists with regard to whether low-level radiation from CT scanning does significantly increase the risk of developing fatal cancer.[41]

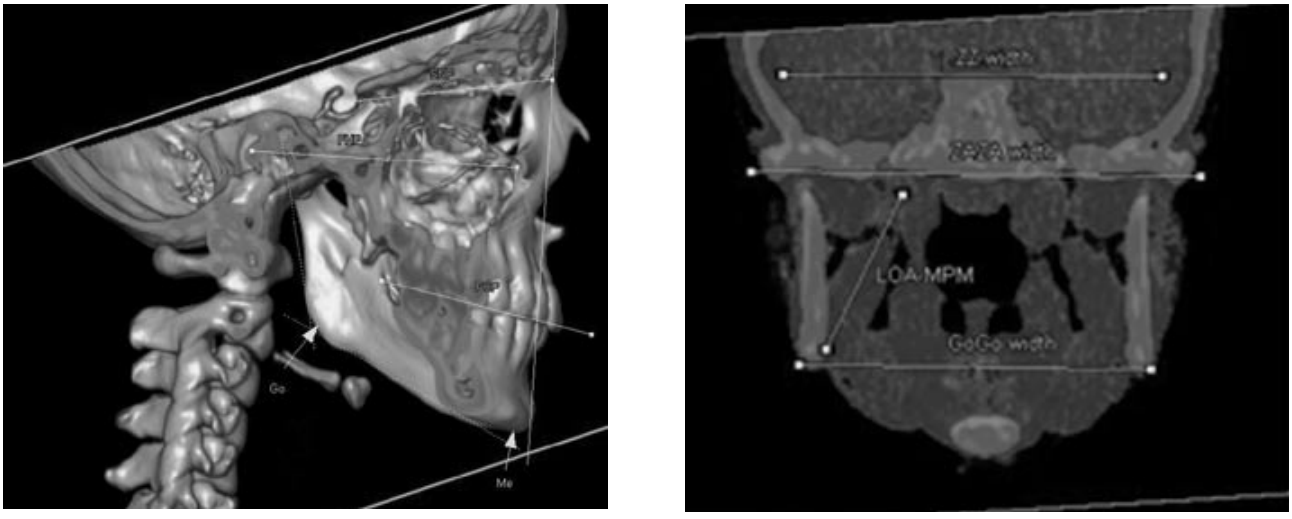
Two main factors that may influence the radiation exposure to the patient would be the X-ray beam energy (determined by tube potential, measured in kilovoltage peak, kVp) and photon fluence (affected by the product of tube current, measured in milliamperes, mA, and time).[5] In contrast to conventional radiography, radiation dose used in CT does not reduce as the incident beam penetrates the body from the periphery to the core. Rather, the radiation dose from a cranial CT examination is more uniformly distributed across the scanning plane with the patient equally irradiated from all directions. Also, other factors such as scattered radiation, the divergence of the radiation beam and limitations in the efficiency of beam collimation may further contribute to additional radiation absorption beyond the boundaries of the scan volume.[5]

Image noise is an important determinant of the CT image quality. Given that it is also inversely affected by X-ray beam energy, strategies for managing radiation risks have been directed toward radiation dose optimisation rather than dose reduction per se. The challenge has therefore been for clinicians to identify acceptable thresholds of image quality to minimise radiation doses and for manufacturers to improve the dose efficiency of their CT systems.[5] The ALARA (as low as reasonably achievable) principle has been suggested for radiation dose minimisation.[41] Appropriate strategies may involve limiting the number of CT examinations, the region of coverage, and customising CT settings based on the indication, the cross-sectional dimensions of the region to be examined and the weight and size of the patient.[5,41,42] Scanning parameters that affect CT radiation dose include the scanner geometry, tube current and voltage, scanning modes, length and collimations, table speed and pitch, gantry rotation time, and shielding.[5,41,43] Most of these parameters can be modulated to obtain the desired image quality.

Other innovations that have served to address the issue of radiation optimisation have included 'pre-patient' tracking or the control of beam collimation and tube focal spot motion; automatic tube current modulation (ATCM); efficient detector configuration; the use of improved filters to reduce 'soft X-rays' and image noise or to increase the filtration of signal dependent noise; and the improvement in image processing algorithms.[5] ATCM is a recent technical innovation that can substantially reduce radiation dose. With automatic adjustments of the tube current to reflect the changing anatomy of the patient, the quantum noise in projections can also be adjusted to maintain a desired noise level on the image and to improve dose efficiency.[5,43]

The annual effective dose limit for continuous or repeated exposures, as established by National Council on Radiation Protection Measurements (NCRP) in the United States, is recommended to be around 1 mSv.[44] For perspective, the average person receives approximately 1–3 mSv of natural background radiation annually.[41,44] The range of radiation exposure values previously reported for cranial CT examination is from 0.15–2.30 mSv.[45–47] Due to the issue of high cost, the size of the equipment and relatively high radiation exposure, cone beam computed tomography (CBCT) has recently been introduced as a 3D dental imaging alternative. The effective radiation dose previously reported for CBCT is from 0.05–1.19 mSv.[45,47–49] It is perhaps generally accepted that the exposure levels from CBCT are typically lower than MDCT.[45,48–50] The image quality of CBCT, however, does not generally correspond to the usual quality of CT.[51,52] CBCT is designed to scan high contrasting structures, typical of osseous structures,[47,50] and is incapable of discriminating soft tissue because of its low contrast resolution.[50,53,54] Initially, the typical field of view with CBCT image is small and similar to the size of a periapical radiograph.[55] Larger image sizes of 13 to 19 cm in height have now been reported, but they may come at the expense of image resolution.[51] In time, further improvement in the CBCT technology should address these issues.

While the effective dose contribution from a panoramic examination (0.01–0.03 mSv[46,49,53,56]) or



Skeletal view

Muscular view

Figure 6. Use of clip planes to display a section or a determined slice thickness of volume data at any given time.

a full-mouth examination (0.03–0.10 mSv[45,46]) is still substantially smaller than either system, exposure levels from low-dose regular dental CT can be significantly reduced to levels comparable with CBCT systems and without the loss of diagnostic image quality.[53,54] Calculations of the actual radiation dose levels found in a 3D-CT study investigated by the present authors showed that the mean radiation dose level for each Melbourne facial morphology scan was 0.37 mSv (± 0.04 mSv).[20] This dose would be within the lower range of radiation dose values reported for CT examinations, still allowing for the accurate assessment of the morphology of the cranial soft tissues and dentoskeletal form. While such a dose may still be higher than that to be expected for routine lateral cephalograms and panoramic radiographs, or perhaps with localised CBCT imaging, dose-reduced MDCT scanning does not necessarily result in excessive radiation exposure, especially when taking into account the multiple diagnostic possibilities associated with a single CT examination.

Measurement of rendered images from 3D-CT

A high precision level and accuracy in the measurement of hard[10–12] and soft tissues[10] using 3D-CT imaging technique is generally accepted. However, a number of factors may affect such accuracy. These include the presence of artefacts, the choice of slice plane, slice thickness and degree of slice overlapping, the window level and width, the matrix size and the chosen rendering technique.[10,19] It is important to note that while 3D-CT images simulate the morphology of the original subject, they are still often viewed in a 2D format on a monitor screen or film; hence providing a perception of the object in three dimensions. Measurements are often considered more reliable if they are made on the rendered images of objects that are oriented in planes whose axes are perpendicular to the perspective of the viewer. Oblique orientations may potentially affect measurement accuracy because of elongation or foreshortening of the image or parallax problems.[57]

Identification and delineation of all soft tissue types

Similar tissue types (e.g. muscles) are defined by a similar range of density values. Therefore, the precise delineation of closely approximated muscle groups is often difficult. Superficial muscles, such as the masseter, are identifiable, but the assessment of deeper components or muscles may be affected (Figure 1). Even with effective transfer functions, visualisation of the internal structures may still be difficult.[13] Such limitations can be minimised by using alternative viewing planes and assessing the CT data in smaller 'cut-out' sections (Figure 6). With the appropriate window level and width settings to selectively filter

out unwanted overlying fatty and skin structures, the delineation of the topography of the mandibular muscles from the transverse or superior plane is possible (Figures 2 and 3). Therefore, not only are the dentoskeletal structures identifiable and measurable with 3D-CT images, but similar accuracy can also be achieved during the assessment of the cross-sectional size and volume of mandibular muscles. While MRI is currently accepted to produce superior soft tissue contrast compared with CT scans, limited literature exists to directly compare the effectiveness of both imaging techniques using the more recent models in the delineation and identification of closely approximated facial muscles.

Logistics and commercial availability of MDCT scanners

MDCT scanners are often limited to specialist imaging practices or hospitals that may perform a large range of CT-related imaging applications, in order to cover the cost of equipment installation. The manipulation of 3D rendering images is also often done with the use of appropriate software developed by the manufacturers and is hence licensed for use only with the purchase of a MDCT scanner. While the processing capacity of a CT workstation is often no different from a typical personal computer, such software is rarely available within an orthodontic practice or clinic. However, it may in the future be possible to purchase extra software licences. Alternatively, other software companies may develop programs which could read the archived CT data format. Auxiliary personnel within an orthodontic practice could also be appropriately trained to analyse the cranial musculoskeletal form.

Conclusions

Despite the limitations outlined above, three-dimensional computed tomography (3D-CT) may, in the future, become a practical technique for the assessment of craniofacial soft and hard tissues in selected dental and surgical cases. 3D-CT provides a more detailed appreciation of the interaction and relationships between the dentoskeletal structures and the overlying soft tissue environment. While progressive advances in this technology would inevitably further improve scanning efficiency while decreasing radiation risk, further research is still be required to determine appropriate scanning protocols for delivering minimal radiation exposure, before the technique can be recommended for routine clinical use. Consideration should also be given to the use of 3D-CT cephalometric analyses including the assessment of the masticatory muscles, since these muscles are now widely accepted to be closely involved in the facial growth and development process, and to influence the predictability and long-term outcomes of clinical treatment.

Acknowledgments

The authors would like to thank Mrs Shona Robertson and Mr Paul Einsiedel from the Department of Radiology at the Royal Melbourne Hospital for their assistance in the application of the 3D-CT technique. This study was supported in part by a grant from the Australian Society of Orthodontists' Foundation for Research and Education.

Corresponding author

Professor Michael Woods
School of Dental Science
The University of Melbourne
720 Swanston Street
Melbourne, Victoria 3010
Australia
Tel: (+61 3) 9341 1497
Fax: (+61 3) 9341 1593
Email: mgwoods@unimelb.edu.au

References

1. Broadbent B. A new X-ray technique and its application to orthodontia. Angle Orthod 1931;1:45–66.
2. Quintero J, Trosien A, Hatcher D, Kapila S. Craniofacial imaging in orthodontics: historical prespective, current status, and future developments. Angle Orthod 1999;69: 491–506.
3. Parks E. Computed tomography applications for dentistry. Dent Clin North Am 2000;44:371–94.
4. Dawn S, Gotway M, Webb W. Multidetector-row spiral computed tomography in the diagnosis of thoracic diseases. Respir Care 2001;46:912–21.
5. Kalra M, Maher M, Toth T, Hamberg L, Blake M, Shepard J et al. Strategies for CT radiation dose optimization. Radiology 2004;230:619–28.
6. Saini S. Multi-detector row CT: principles and practice for abdominal applications. Radiology 2004;233:323–7.
7. Hausleiter J, Meyer T, Hadamitzky M, Huber E, Zankl M, Martinoff S et al. Radiation dose estimates from cardiac multislice computed tomography in daily practice: impact of different scanning protocols on effective dose estimates. Circulation 2006;113:1305–10.

8. Sun Z, Jiang W. Diagnostic value of multislice computed tomography angiography in coronary artery disease: a meta-analysis. Eur J Radiol 2006;60:279–86.
9. Hajeer M, Millett D, Ayoub A, Siebert J. Applications of 3D imaging in orthodontics: Part I. J Orthod 2004;31:62–70.
10. Cavalcanti M, Rocha S, Vannier M. Craniofacial measurements based on 3D-CT volume rendering: implications for clinical applications. Dentomaxillofac Radiol 2004;33: 170–6.
11. Matteson S, Bechtold W, Phillips C, Staab E. A method for three-dimensional image reformation for quantitative cephalometric analysis. J Oral Maxillofac Surg 1989;47: 1053–61.
12. Hildebolt C, Vannier M, Knapp R. Validation study of skull three-dimensional computerized tomography measurements. Am J Phys Anthropol 1990;82:283–94.
13. Halazonetis D. From 2-dimensional cephalograms to 3-dimensional computed tomography scans. Am J Orthod Dentofacial Orthop 2005;127:627–37.
14. Kawamata A, Ariji Y, Langlais R. Three-dimensional computed tomography imaging in dentistry. Dent Clin North Am 2000;44:395–410.
15. Luka B, Brechtelsbauer D, Gellrich N-C, König M. 2D and 3D CT reconstructions of the facial skeleton: an unnecessary option or a diagnostic pearl? Int J Oral Maxillofac Surg 1995;24:76–83.
16. Udupa J. Three-dimensional visualization and analysis methodologies: a current prespective. Radiographics 1999; 19:783–806.
17. Ariji Y, Kawamata A, Yoshida K, Sakuma S, Nawa H, Fujishita M et al. Three-dimensional morphology of the masseter muscle in patients with mandibular prognathism. Dentomaxillofac Radiol 2000;29:113–8.
18. Kitai N, Fujii Y, Murakami S, Furukawa S, Kreiborg S, Takada K. Human masticatory muscle volume and zygomatico-mandibular form in adults with mandibular prognathism. J Dent Res 2002;81:752–6.
19. Katsumata A, Fujishita M, Ariji Y, Ariji E, Langlais R. 3D CT evaluation of masseter muscle morphology after setback osteotomy for mandibular prognathism. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2004;98:461–70.
20. Chan HJ, Woods M, Stella D. Mandibular muscle morphology in growing children with different vertical facial patterns: a 3D-CT study. Am J Orthod Dentofacial Orthop 2007 (in press).
21. Swennen G, Schutyser F. Three-dimensional cephalometry: spiral multi-slice vs cone-beam computed tomography. Am J Orthod Dentofacial Orthop 2006;130:410–6.
22. Macchi A, Carrafiello G, Cacciafesta V, Norcini A. Three-dimensional digital modeling and setup. Am J Orthod Dentofacial Orthop 2006;129:605–10.
23. Troulis M, Everett P, Seldin E, Kikinis R, Kaban L. Development of a three-dimensional treatment planning system based on computed tomographic data. Int J Oral Maxillofac Surg 2002;31:349–57.
24. Girod S, Keeve E, Girod B. Advances in interactive craniofacial surgery planning by 3D simulation and visualization. Int J Oral Maxillofac Surg 1995;24:120–5.
25. Xia J, Wang D, Samman N, Yeung R, Tideman H. Computer-assisted three-dimensional surgical planning and simulation: 3D color facial model generation. Int J Oral Maxillofac Surg 2000;29:2–10.
26. Katsumata A, Fujishita M, Maeda M, Ariji Y, Ariji E, Langlais R. 3D-CT evaluation of facial asymmetry. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2005;99: 212–20.
27. Papadopoulos M, Christou P, Athanasiou A, Boettcher P, Zeilhofer H, Sader R et al. Three-dimensional craniofacial reconstruction imaging. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2002;93:382–93.
28. Jacobs R, Adriansens A, Verstreken K, Suetens P, van Steenberghe D. Predictability of a three-dimensional planning system for oral implant surgery. Dentomaxillofac Radiol 1999;28:105–11.
29. Cavalcanti M, Ruprecht A, Vannier M. 3D volume rendering using multislice CT for dental implants. Dentomaxillofac Radiol 2002;31:218–23.
30. Holst S, Blatz M, Eitner S. Precision for computer-guided implant placement: using 3D planning software and fixed intraoral reference points. J Oral Maxillofac Surg 2007;65: 393–9.
31. van Steenberghe D, Glauser R, Blomback U, Andersson M, Schutyser F, Pettersson A et al. A computed tomographic scan-derived customized surgical template and fixed prosthesis for flapless surgery and immediate loading of implants in fully dentulous maxillae: a prospective multicenter study. Clin Implant Dent Relat Res 2005;7 Suppl 1:S111–20.
32. Ono I, Ohura T, Narumi E, Kawashima K, Matsuno I, Nakamura S et al. Three-dimensional analysis of craniofacial bones using three-dimensional computer tomography. J CranioMaxillofac Surg 1992;20:49–60.
33. Salvolini U. Traumatic injuries: imaging of facial injuries. Eur Radiol 2002;12:1253–61.
34. Kawamata A, Fujishita M, Nagahara K, Kanematu N, Niwa K, Langlais R. Three-dimensional computed tomography evaluation of postsurgical condylar displacement after mandibular osteotomy. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1998;85:371–6.
35. Kawamata A, Fujishita M, Ariji Y, Ariji E. Three-dimensional computed tomographic evaluation of morphologic airway changes after mandibular setback osteotomy for prognathism. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2000;89:278–87.
36. Fairburn S, Waite P, Vilos G, Harding S, Bernreuter W, Cure J et al. Three-dimensional changes in upper airways of patients with obstructive sleep apnea following maxillomandibular advancement. J Oral Maxillofac Surg 2007;65: 6–12.
37. Katsumata A, Nojiri M, Fujishita M, Ariji Y, Ariji E, Langlais R. Condylar head remodeling following mandibular setback osteotomy for prognathism: a comparative study of different imaging modalities. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2006;101:505–14.
38. Gerhard S, Ennemoser T, Rudisch A, Emshoff R. Condylar injury: magnetic resonance imaging findings of temporomandibular joint soft tissue changes. Int J Oral Maxillofac Surg 2007;36:214–8.
39. Şener S, Akganlü F. MRI characteristics of anterior disc displacement with and without reduction. Dentomaxillofac Radiol 2004;33:245–52.
40. Hatcher D, Aboudara C. Diagnosis goes digital. Am J Orthod Dentofacial Orthop 2004;125:512–5.
41. Frush D, Donnelly L, Rosen N. Computed tomography and radiation risks: what pediatric health care providers should know. Pediatrics 2003;112:951–7.
42. Wilting J, Zwartkruis A, van Leeuwen M, Timmer J, Kamphuis A, Feldberg M. A rational approach to dose reduction in CT: individualized scan protocols. Eur Radiol 2001;11: 2627–32.

43. Kalra M, Maher M, Toth T, Schmidt B, Westerman B, Morgan H et al. Techniques and applications of automatic tube current modulation for CT. Radiology 2004;233: 649–57.
44. Mupparapu M. Radiation protection guidelines for the practicing orthodontist. Am J Orthod Dentofacial Orthop 2005; 128:168–72.
45. Mah J, Danforth R, Bumann A, Hatcher D. Radiation absorbed in maxillofacial imaging with a new dental computed tomography device. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2003;96:508–13.
46. Ngan D, Kharbanda O, Geenty J, Darendeliler M. Comparison of radiation levels from computed tomography and conventional dental radiographs. Aust Orthod J 2003; 19:67–75.
47. Wörtche R, Hassfeld S, Lux C, Müssig E, Hensley F, Krempien R et al. Clinical application of cone beam digital volume tomography in children with cleft lip and palate. Dentomaxillofac Radiol 2006;35:88–94.
48. Hashimoto K, Arai Y, Iwai K, Araki M, Kawashima S, Terakado M. A comparison of a new limited cone beam computed tomography machine for dental use with a multidetector row helical CT machine. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2003;95:371–7.
49. Ludlow J, Davies-Ludlow L, Brooks S. Dosimetry of two extraoral direct digital imaging devices: NewTom cone beam CT and Orthophos Plus DS panoramic unit. Dentomaxillofac Radiol 2003;32:229–34.
50. Schulze D, Heiland M, Thurmann H, Adam G. Radiation exposure during midfacial imaging using 4- and 16-slice computed tomography, cone beam computed tomography systems and conventional radiography. Dentomaxillofac Radiol 2004;33:83–6.
51. Araki K, Maki K, Seki K, Sakamaki K, Harata Y, Sakaino R et al. Characteristics of a new developed dentomaxillofacial x-ray cone beam CT scanner (CB MercuRayTM): system configuration and physical properties. Dentomaxillofac Radiol 2004;33:51–9.
52. Holberg C, Steinhäuser S, Geis P, Rudzki-Janson I. Cone-beam computed tomography in orthodontics: benefits and limitations. J Orofac Orthop 2005;66:434–44.
53. Cohnen M, Kemper J, Möbes O, Pawelzik J, Mödder U. Radiation dose in dental radiology. Eur Radiol 2002;12: 634–7.
54. Rustemeyer P, Streubühr U, Suttmoeller J. Low-dose dental computed tomography: significant dose reduction without loss of image quality. Acta Radiol 2004;45:847–53.
55. Arai Y, Tammisalo E, Iwai K, Hashimoto K, Shinoda K. Development of a compact computed tomographic apparatus for dental use. Dentomaxillofac Radiol 1999;28:245–8.
56. Gijbels F, Jacobs R, Bogaerts R, Debaveye D, Verlinden S, Sanderink G. Dosimetry of digital panoramic imaging. Part I: patient exposure. Dentomaxillofac Radiol 2005;34:145–9.
57. Covino SW, Mitnick RJ, Shprintzen RJ, Cisneros GJ. The accuracy of measurements of three-dimensional computed tomography reconstructions. J Oral Maxillofac Surg 1996; 54:982–90. Discussion 990–1.