FEATURES SECTION

Current Products and Practice

Three-dimensional cone beam computerized tomography in orthodontics

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There has been an escalating interest in three-dimensional imaging devices over the last decade. Orthodontists are beginning to appreciate the advantages that the third dimension gives to clinical diagnosis, treatment planning and patient education. This article focuses on the cutting edge technology of cone beam CT, which utilizes conventional X-ray technology and computerized volumetric reconstruction to reproduce a three-dimensional image. A variety of applications and range of issues associated with this technology will be discussed.

Key words: Cone beam, tomography, imaging, orthodontics, three-dimensional

Introduction

Cone beam computerized tomography (CBCT) was developed in the 1990s as an evolutionary process resulting from the demand for three-dimensional (3D) information obtained by conventional computerized tomography (CT) scans. Custom built cranio-maxillofacial CBCTs started to appear in the market over the last decade and a variety of applications to the facial and dental environments have been established. In recent times, there have been a number of pilot studies and reports of its clinical usages but experts believe that this technology is still in its infancy.[1]

This article hopes to give a brief introduction to CBCT technology and explore a number of issues regarding its usage in an orthodontic and clinical setting.

Conventional computerized tomography (CT)

Computerized tomography was developed by Sir Godfrey Hounsfield in 1967 and since the first prototype, there has been a gradual evolution to five generations of such systems. The method of classification for each system is based on the organization of the individual parts of the device and the physical motion of the beam in capturing the data. First generation scanners consisted of a single radiation source and a single detector. The information was obtained slice by slice (Figure 1a). The second generation was introduced as an improvement and multiple detectors were incorporated within the plane of the scan. However, these detectors were not necessarily continuous nor did they span the diameter of the object. The third generation was made possible by the advancement in detector and data acquisition technology. These large detectors reduced the need for the beam to translate around the object to be measured and were often known as the 'fan-beam' CTs. Ring artefacts were often seen on the images captured distorting the three-dimensional image and obscuring certain anatomical landmarks. The fourth generation was developed to counter this problem. A moving radiation source and a fixed detector ring were introduced. This meant that modifications to the angle of the radiation source had to be taken into account and more scattered radiation was seen. Finally, the fifth and sixth generation scanners were introduced to reduce 'motion' or 'scatter' artefacts. As with the previous two generations, the detector is stationary and the electron beam is electronically swept along a semicircular

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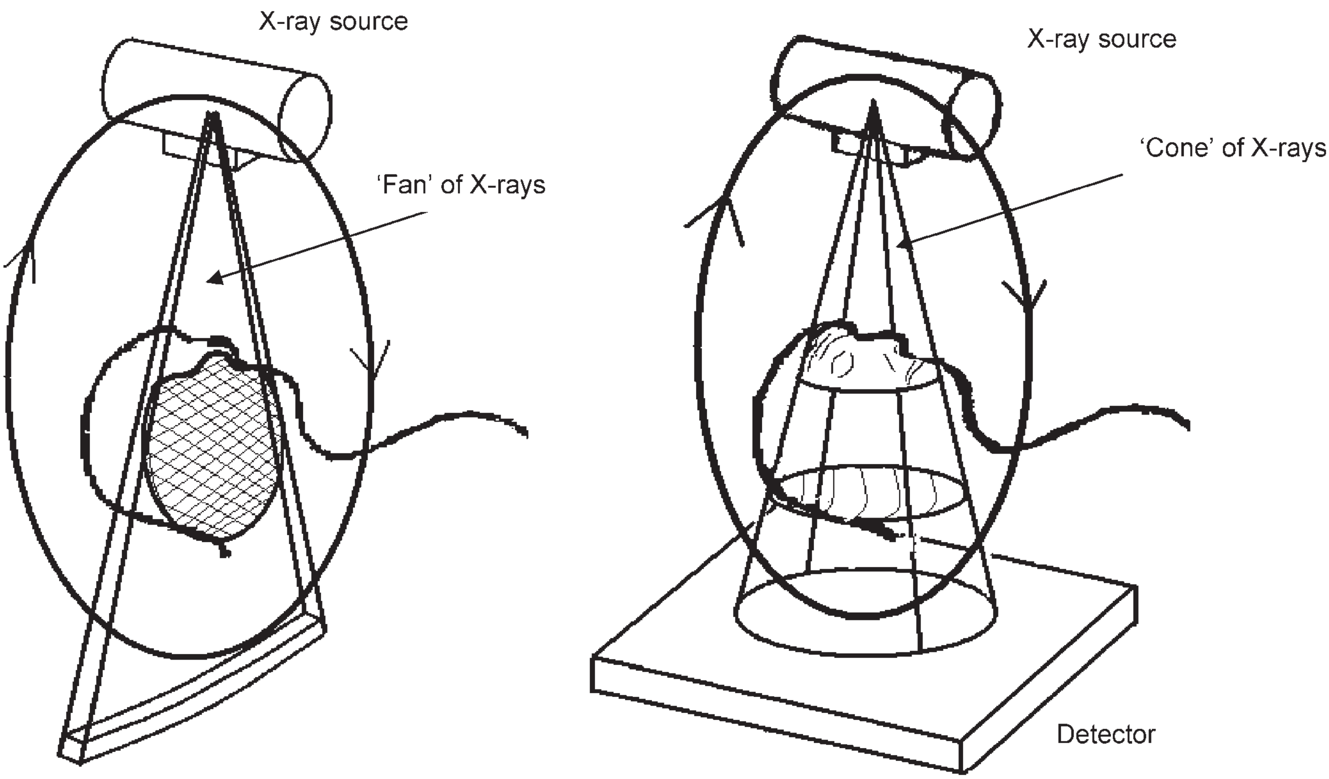


Figure 1 Diagrammatic representation of image capture technique of CT and CBCT devices (Courtesy of Mr Arun Singh, Imaging Sciences, Hatfield PA, USA)

tungsten strip anode. The radiation is produced at the point where the electron beam hits the anode and results in a source of X-rays that rotates about the patient with no translation components or moving parts. Projections of the X-rays are so rapid that even the heart beats of a person may be captured. This has led some clinicians to hail it as a 4D motion capture device.

Nevertheless, there are several limitations with these systems. They require a considerable physical space and are much more expensive than conventional radiographic machines. The images captured on the detector screens are made up of multiple slices, which are 'stacked' to obtain a final complete image making it time consuming and less cost efficient. In orthodontics, the radiation exposure to the patient was partially responsible in limiting the CT usage to complex craniofacial problems and specialized diagnostic information.

CBCT

Craniofacial CBCTs were designed to counter some of the limitations of the conventional CT scanning devices.[2] The object to be evaluated is captured as the radiation source falls onto a two-dimensional detector. This simple difference allows a single rotation of the radiation source to capture an entire region of interest, as compared to conventional CT devices where multiple slices are stacked to obtain a complete image (Figure 1).[3] The cone beam also produces a more focused beam and considerably less scatter radiation compared to the conventional fan-shaped CT devices.[4] This significantly increases the X-ray utilization and reduces the X-ray tube capacity required for volumetric scanning.[5] It has been reported that the total radiation is approximately 20% of conventional CTs and equivalent to a full mouth peri-apical radiographic exposure.[6]

These component innovations are significant and allow the CBCT to be less expensive and smaller. Furthermore, the exposure chamber (i.e. head), is custom built and reduces the amount of radiation. The images are comparable to the conventional CTs and may be displayed as a full head view, as a skull view or regional components.

CBCT acquisition systems

There are currently four main system providers in the world market:

- NewTom 3G (Quantitative Radiology, Verona, Italy),

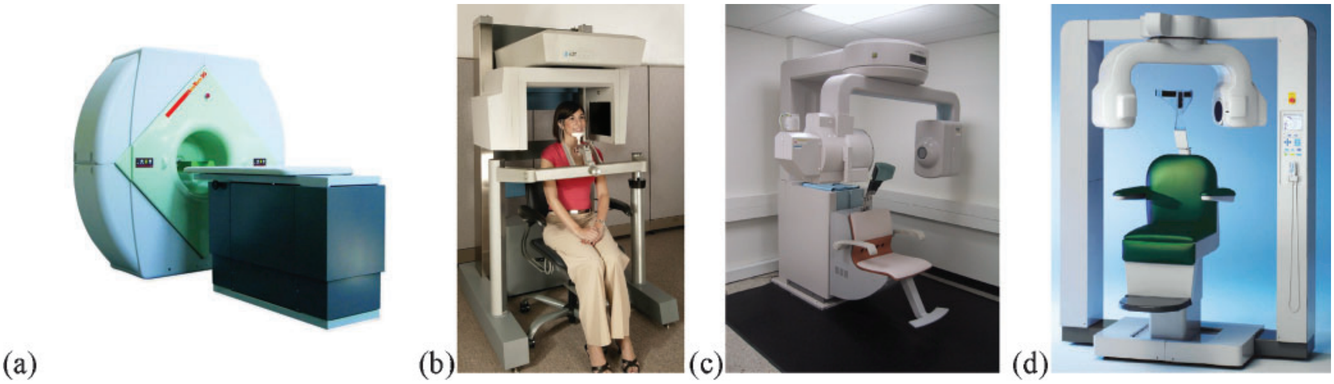


Figure 2 Currently available cone beam scanners approved for use in dental medicine: (a) NewTom 3G (courtesy of Aperio Services LLC – Sarasota – FL, USA). (b) IS i-CAT (courtesy of Imaging Sciences, Hatfield PA, USA). (c) Hitachi CB MercuRay (courtesy of Hitachi Medical System America Inc., Twinsburg, OH, USA). (d) J. Morita three-dimensional Accuitomo (courtesy of J. Morita USA, Irvine, CA, USA)

- i-CAT (Imaging Sciences International, Hatfield, USA),
- CB MercuRay (Hitachi Medical Corporation, Tokyo, Japan),
- 3D Accuitomo (J Morita Mfg Corp, Kyoto, Japan).

As clinical research in this technology escalates and as the cost reduces, there is no doubt that more providers will start to invest and promote this technology.

The available CBCT machines differ in size, possible settings, area of image capture (field of view), and clinical usage (Table 1).

NewTom 3G

The family of NewTom 3G (Quantitative Radiology, Verona, Italy) devices (Figure 2a) was introduced

Table 1 Specification of the currently available cone beam CT machines approved for use in dentistry

Trade name	NewTom	i-CAT™ Cone beam 3-D Dental Imaging System	CB MercuRay™	3D Accuitomo XYZ Slice View Tomograph
Manufacturer	Quantitative Radiology, Verona, Italy	Imaging Sciences, Hatfield PA, USA	Hitachi Medical Corporation, Tokyo, Japan	J Morita Mfg Corp, Kyoto, Japan
Model	NewTom 3G	i-CAT	MercuRay	MCT-1
Main unit dimensions	2000(W) × 2413 (D) × 2000 mm (H)	1040(W) × 1120 (D) × 1830 mm (H)	1840(W) × 1900 (D) × 2250 mm (H)	1620(W) × 1200 (D) × 2080 mm (H)
Weight	480 kg		950 Kg	400 Kg
Tube voltage	110 kVP	120 kVP	60–120 kVP	60–80 kVP
Tube current	15 mA	3–8 mA	10–15 mA	1–10 mA
Scan time*	36 seconds	10–40 seconds	10 seconds	17 seconds
Image detector	Image intensifier CCD	Amorphous flat panel detector	Image intensifier CCD	Image intensifier CCD
Grayscale	12 bit	12 bit	12 bit	8 bit
Field of view	100 mm (6-inch)	250 (diameter) × 200 (height) mm	102.4 mm (6-inch)	40 (diameter) × 30 (height) mm
	150 mm (9-inch)		150 mm (9-inch)	
	200 mm (12-inch)		190 mm (12-inch)	
Voxel size	0.2–0.4 mm	0.2–0.4 mm	0.2–0.376 mm	0.125 mm
Reconstruction time	2 minutes	1.5 minute	6 minutes	5 minutes
Suggested price	£ 146, 000	£ 97, 000	£ 159,400	£ 103,600
Website addresses	www.qrverona.it	www.imagingsciences.com	www.hitachimed.com	www.jmorita-mfg.com

*Scan time is how long the machine takes to take an image, and does not represent exposure time. For example, in the NewTom even though the scan time is 36 seconds, the actual exposure time is only 5.4 seconds recently as part of an evolutionary process from its predecessor the NewTom 9000. The NewTom was the first device in the dental market to use CBCT technology.

The system operates in a similar way to a conventional CT. The patient is imaged in a supine position, and scans of the head and neck are completed within 36 seconds. The system offers three possible fields of views. The manufacturers claim the system is able to produce a voxel resolution up to 0.125 mm when using the smaller field of view.

The voxel (volume pixel) represents a quantity of three-dimensional data, just as a pixel represents a point or cluster of points in two-dimensional data. The voxel resolution gives an indication of the ability to capture the finer details in a scan (e.g. the periodontal ligament is on average 0.5 mm wide and, therefore, in order to capture this detail a minimum of two voxels with a resolution of 0.25 mm is required).

Custom built software allows volumetric and surface area analysis of soft and hard tissues. These datasets may be exported into a standard Digital Imaging and Communications in Medicine (DICOM) 3-D format for image manipulation.

i-CAT

The i-CAT cone beam three-dimensional imaging system is developed by Imaging Sciences International (Imaging Sciences, Hatfield PA, USA) (Figure 2b). The three-dimensional image is captured with the patient sitting upright as in any standard OPT machine and the scan time varies from 20–40 seconds.

In the initial prototypes, only the maxillo-mandibular regions could be imaged, but with new improvements and modifications, the manufacturers now claim that a field of view of 20×25 cm may be obtained. This is sufficient to capture a standard facial image equivalent to that of a three-dimensional lateral cephalogram.

The manufacturers claim that the novel amorphous silicon flat panel detector provides no distortion, a 12-bit grayscale and a pixel size resolution of 0.125 mm. The flat panel provides good contrast and a long panel life, thus making better clinical images, while being cost effective.

One early criticism of the system was the distortion of the facial tissues produced by the chin rest when the patient was positioned in the device. This feedback has led the company to improve the patient posturing device and no such problems arise in the later versions of the system.

CB MercuRay

The CB MercuRay (Hitachi Medical Corporation, Tokyo, Japan) is the latest addition to the full view head and neck imaging CBCTs (Figure 2c).

The X-ray source is made of a low energy fixed anode tube producing a cone-shaped X-ray beam that is captured on an image intensifier and a solid state CCD. The manufacturers claim a scan time of 10 seconds through a rotation of 360° that provides 288 views that can be seen either as 2-D or 3-D. The CB MercuRay offers three different fields of view and is the fastest CBCT machine currently available. This is an advantage in reducing patient movement during image capture.

3D Accuitomo

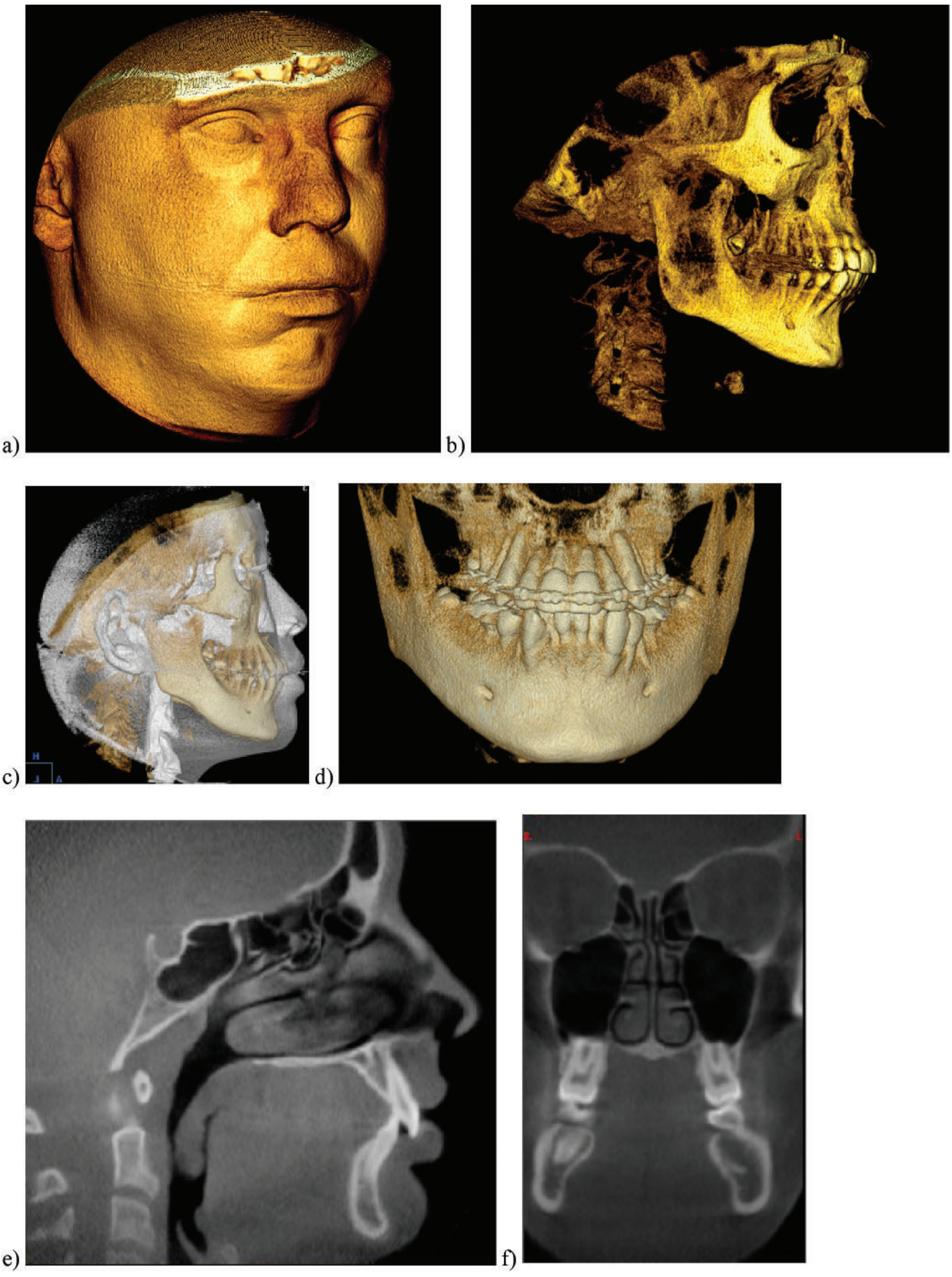
The 3D Accuitomo (J. Morita Mfg Corp, Kyoto, Japan) was developed as a collaboration between the School of Dentistry at Nihon University and J Morita MfG Corp (Figure 1d). The field of view of 30×40 mm focuses on more regional and specific anatomical investigations. The smaller field of view results in a reduced effective radiation of 7.4 μSv. This small and compact unit has the advantage of only requiring 1.6 times the space of a dental panoramic X-ray unit (1620×1200 mm).

Clinical applications of orthodontic interest

With CBCT technology all possible radiographs can be taken in under 1 minute. The orthodontist now has the diagnostic quality of periapicals, panoramic, cephalograms and occlusal radiographs, and TMJ series at their disposal, along with views that cannot be produced by regular radiographic machines like axial views, and separate cephalograms for the right and left sides (Figure 3). A number of clinical applications have already been reported in the literature.[5]

Impacted teeth and oral abnormalities

The incidence of maxillary ectopic cuspids occurs in approximately 3% of the population. The distribution and location has been reported at 80% palatally and 20% buccally. The tube shift method (also known as the parallax technique) has been the traditional method of locating these cuspids and provides an arbitrary position and approximation of the level of difficulty for the management of the cuspid. This investigative technique uses two conventional radiographs and the location of the tooth identified by the movement of the objects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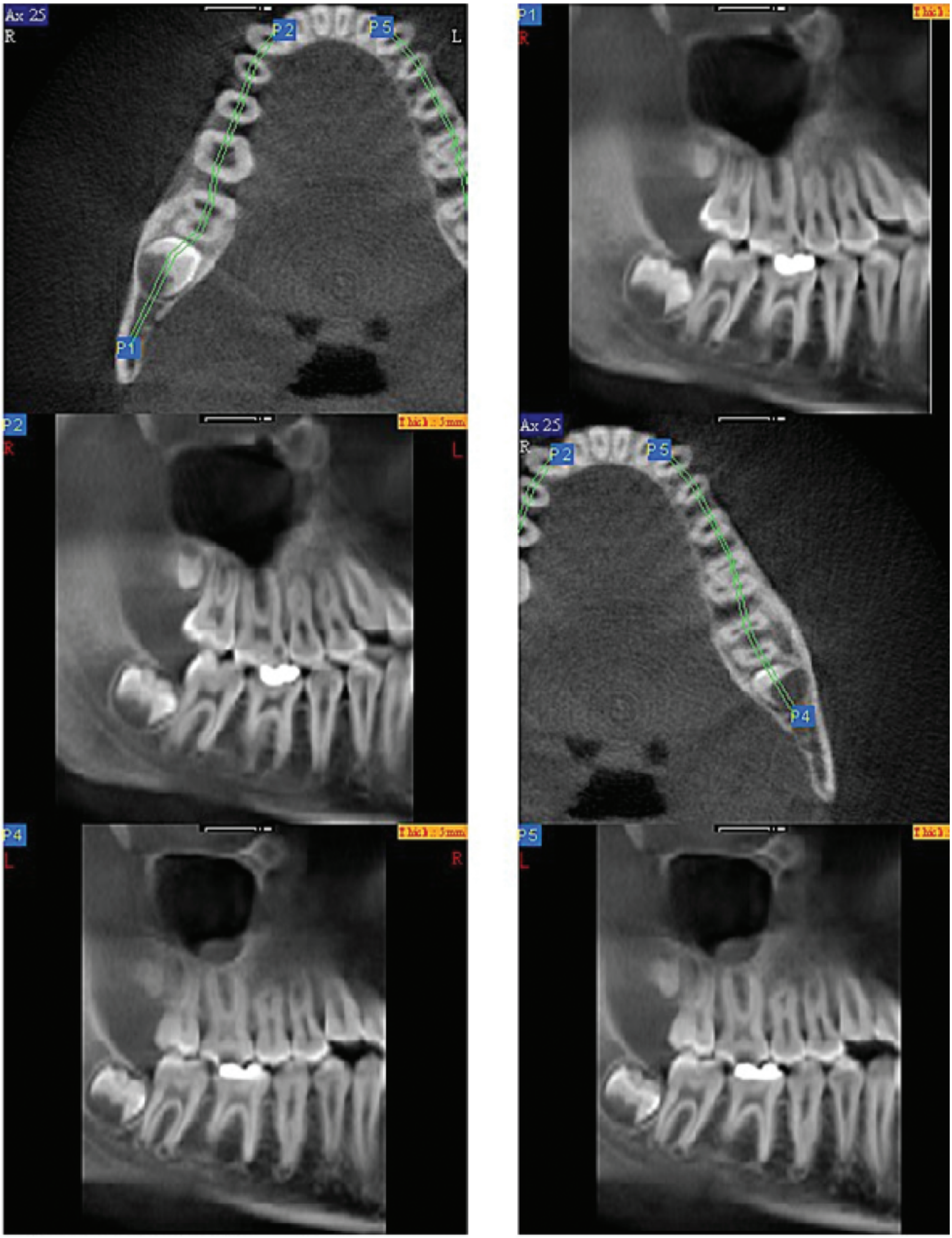

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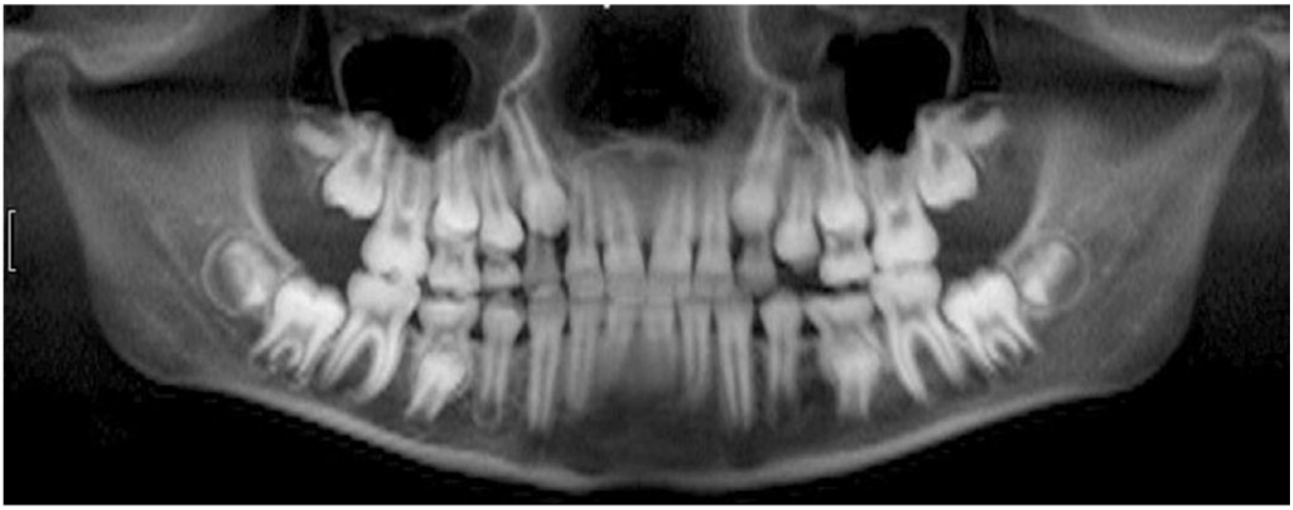

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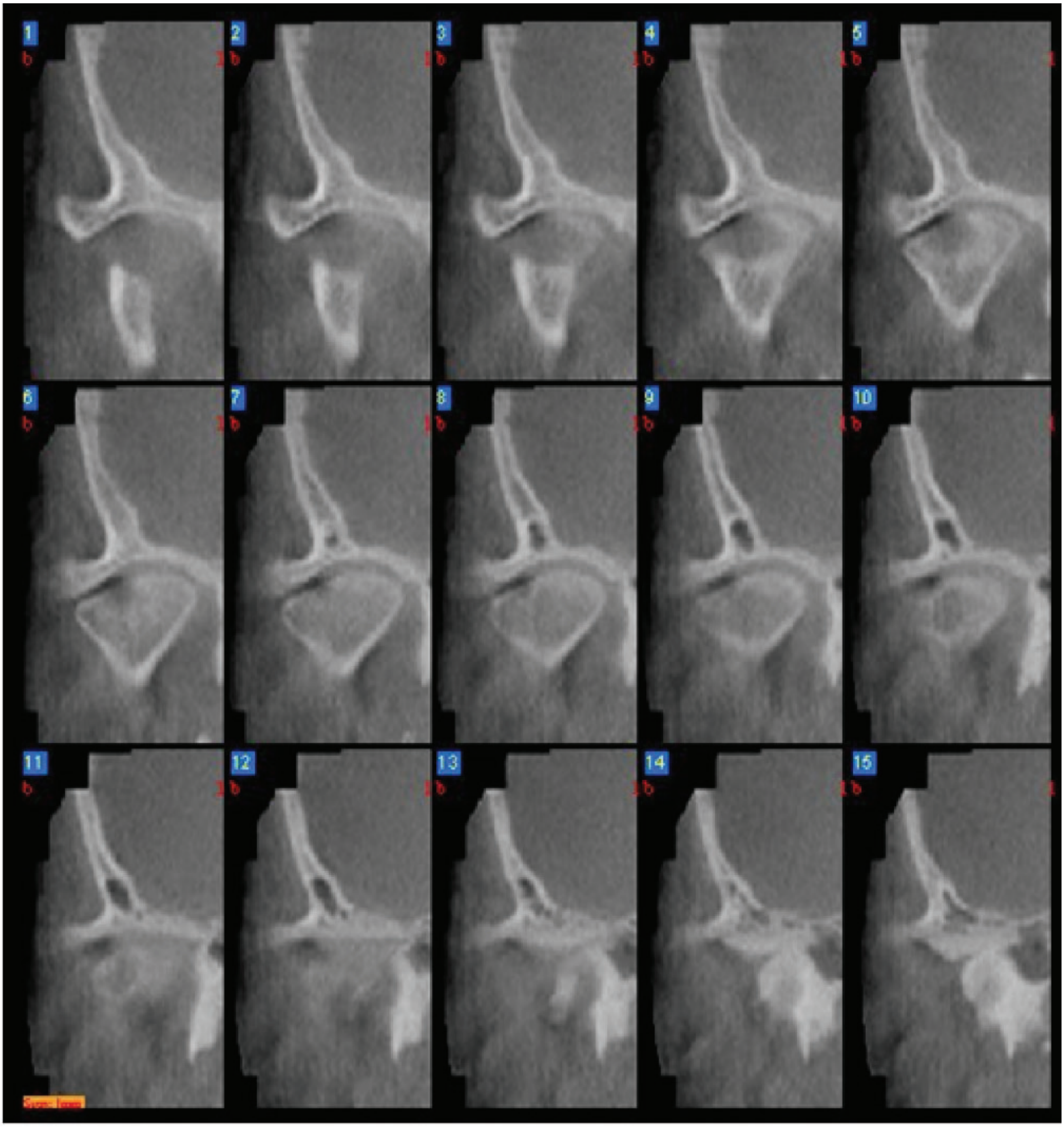

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Figure 3 Images taken with a CBCT scanner (courtesy of Aperio Services LLC, Sarasota, FL, USA; and Hitachi Medical System America Inc., Twinsburg, OH, USA). (a) Soft tissue face. (b) Maxillofacial skeleton with fixed appliances in maxillary posterior dentition. (c) Soft tissue face and maxillofacial skeleton in the same view. (d) Image of patient with upper fixed appliances. (e) sagittal view of maxillofacial complex. (f) Coronal view of the posterior dentition. (g) Image equivalent to bite wing series. (h) Image equivalent to panoramic radiograph, using a 2 mm slice. (i,j) Image equivalent to traditional cephalograms, but with CBCT both left and right sides can be analysed and traced separately (an image equivalent to a traditional cephalogram can also be achieved by superimposing right and left structures into a single image). (k) A study series on a mandibular condyle. (l) TMJ area respectively to the way in which the radiograph was taken. In addition, the extent of the pathology caused by the ectopic tooth and its surrounding structures has also been evaluated by these radiographs.[7] However, clinical reports using three-dimensional conventional CT scans have shown that the incidence of root resorption to the adjacent teeth has been larger than previously thought.[8]

A recent report found that the use of CBCT technology could add value to the management of patients with such anomalies.[9] The authors used the technology to precisely locate the ectopic cuspids and to design treatment strategies that allowed for minimally invasive surgery to be performed and helped to design effective orthodontic strategies.

Another interesting use of the CBCT is the location of incidental oral abnormalities in patients. Some centres in the USA have begun to adopt CBCT imaging into routine dental examination procedures. Initial reports have suggested that there were higher incidences of oral abnormalities than previously suspected (i.e. oral cysts, ectopic/buried teeth and supernumeraries).

The value of these findings must be taken with caution, as the number of elective treatments that may be carried out may be limited. This leads to the question of whether to intervene in every abnormality located on these three-dimensional images and the extent to which the patient needs to be informed. In the event that these abnormalities were to lead to pathological episodes, what responsibilities would the clinician and patient hold in the decision making process? This could lead to a host of future medico-legal problems on how clinicians and patients manage the information.

Airway analysis

The CBCT technology provides a major improvement in the airway analysis, allowing for its three-dimensional and volumetric analysis.

Airway analysis has conventionally been carried out by using lateral cephalograms. A recent study carried on 11 subjects, using lateral cephalograms and CBCT imaging found that there was moderate variability in the measurements of upper airway area and volume.[10]

Three-dimensional airway analysis will no doubt be useful in understanding the reasons why clinical conditions like sleep apnoea and enlarged adenoids affect the way clinicians manage these complex conditions.

Assessment of alveolar bone heights and volume

Implantologists have long appreciated the third dimension in their clinical work. Conventional CT scans are used routinely to assess bone dimensions, bone quality and alveolar height, especially when multiple units are proposed. This has improved the clinical success of these prostheses, and led to more accurate and aesthetic outcomes in oral rehabilitation.

The introduction of CBCT technology means that both the cost and effective radiation dose can be reduced, suggesting that its frequency of use may increase. The CBCT has already been in use in implant therapy[11] and may be exploited in orthodontics for the clinical assessment of bone graft quality following alveolar surgery in patients with cleft lip and palate.[12] The images produced resulted in greater precision in the evaluation of bone sites and, therefore, gave the clinician a better chance of restoring the site with implants and also influenced the decision-making process of whether to move teeth orthodontically into the repaired alveolus.

Temporomandibular joint (TMJ) morphology

Condylar resorption occurs in 5–10% of patients who undergo orthognathic surgery. Recent three-dimensional studies have tried to understand how the condyle remodels and preliminary data suggests that much of the condylar rotation resulting in remodelling is a direct result of the surgical procedures alone.[13] TMJ changes following distraction osteogenesis treatment and dento-facial orthopaedics still need further study.

The quality of the images of the TMJ with CBCT machines is comparable to conventional CTs, but the image taking is faster, less expensive, and provide less radiation exposure. This has opened a new avenue for imaging the TMJ.[14]

Radiation exposure

Even though the cone beam technology is able to provide three-dimensional volumetric images with up to four times less radiation than a conventional CT,[15] the resulting effective radiation is dependent on the settings used (kVp and mA). The use of lower mAs and/or collimation are some of the ways to reduce the amount of radiation the patient receives, but at the same time can produce a lower image quality than by using higher settings. Patient effective exposure dose from a CBCT machine has been reported to be as low as 45 μSv to as high as 650 μSv. As a reference, published exposure for an analogue full mouth series has been reported as 150 μSv;[16] for an analogue panoramic radiograph as 54 μSv[17] and a round trip from Paris to Tokyo adds 139 μSv of effective dose to each passenger.[18,19]

In 2001, an article associating the use of conventional CT in children to radiation-induced fatal cancer[20] raised some controversial concepts. As a result, CTs were adjusted to have a decrease in effective dose from 6000 to 2600 μSv.[21] Even at the highest settings and best image quality possible, none of the CBCT machines come close to those values.

The British Orthodontic Society Guidelines suggests that: 'Radiographs should only be justified when the management of patient is dependent on the information obtained'.[22] The ADA Council on Scientific Affairs recommends the use of techniques that would reduce the amount of radiation received during dental radiography. Known as the 'As Low As Reasonably Achievable', or ALARA, principle, this includes taking radiographs based on the patient's needs (as determined by an examination), using the fastest film compatible with the diagnostic task, collimating the beam to a size as close to that of the film as feasible and using leaded aprons and thyroid shields.

An accepted ratio between exposure and image quality needs to be reached in order to use the ALARA principle. Depending on the objective and desired outcome, alternative technologies should be explored since they may offer a less invasive three-dimensional technology.[23–27] Figure 4 demonstrates soft tissue scans of a growing patient analysed every 6 months and is produced using two Minolta VI 900 laser scanners and RapidForm™ Imaging Software.

Other matters

The CBCT is excellent for imaging hard tissues structures and most soft tissue components. However, it does not have the ability to map out exactly the muscle structures and their attachments. These intricate structures would have to be imaged using conventional magnetic resonance imaging (MRI) technology, which (incidentally) does not predispose the patient to radiation exposure.

The CBCT soft tissue images do not capture the true colour texture of the skin. Therefore, in order to obtain photographic quality resolution, manipulation of the images is still required. Successful attempts to map tissue texture maps onto conventional CTs have been reported and may be similarly applied to this new technology.[28] When they become available, perhaps they can successfully replace the photographs also taken during records. Another criticism made is the long capture time for a full view of a subject (scan time of 30–40 seconds), during which involuntary muscle movements (nostrils and breathing) will lead to inaccuracies to soft tissue capture. These limitations mean that the three-dimensional devices like stereo-photogrammetry and laser scanning are still the state of the art in soft tissue texture capture.

As with all new clinical equipment, cost is often a deciding factor. This is more significant to small and

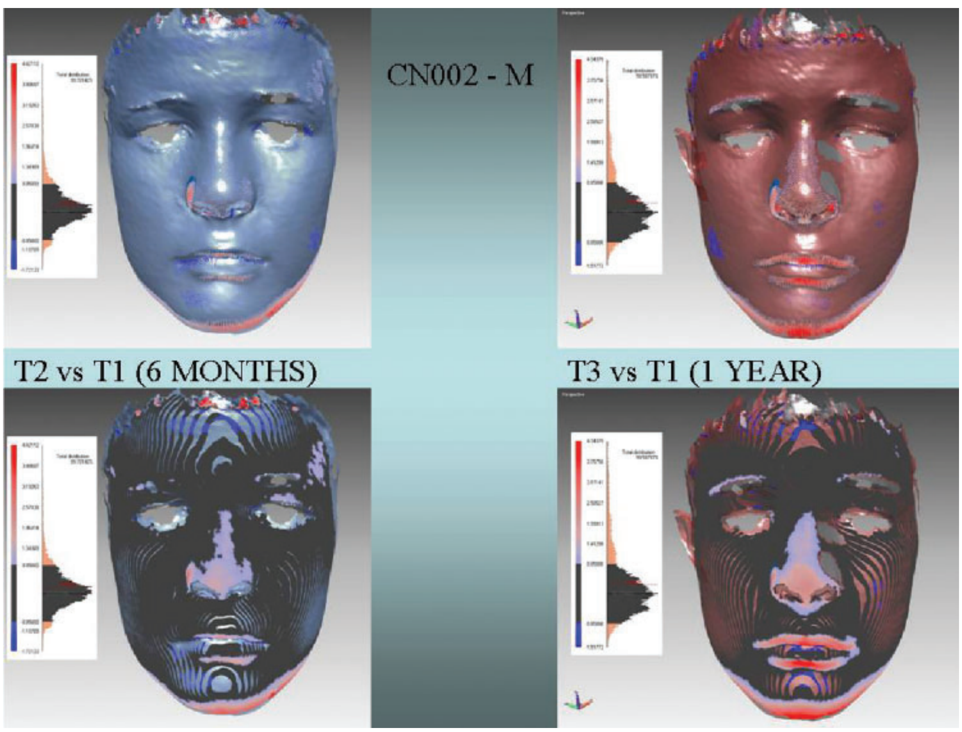

Figure 4 Use of three-dimensional non-invasive soft tissue imaging devices to study longitudinal growth changes in children

private specialized dental practices. All the four companies sell the CBCT devices as a standard base package and additional peripherals can increase the cost. These peripherals are often important to increase the field of view of the image capture or to improve the detector quality. There is also a substantial post-purchase maintenance that goes into each system. These are essential to the effective operation and optimal functioning of the system. Some companies may charge a premium in their maintenance packages and recover their costs in such a manner. So be sure to discuss this with the sales representative and add it on to the budget planning requirements. Finally, as no regulations have been implemented for the usage of these equipment, a budget may need to be set aside for the employment of a specially trained person to take these images.

Conclusion

The long awaited incorporation of the third dimension to our radiographic records is now a reality. There is still room for improvement, however the CBCT technology appears to be here to stay.

The future in orthodontic imaging seems exciting as we discover new frontiers, and as the paradigm in orthodontics shifts from landmarks, lines, distances and angles to surfaces, areas and volumes.

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