Implant dentistry in the digital dental world

Computer aided design/computer aided manufacturing (CAD/CAM) is rapidly transforming the planning, placing and restoring of dental implants. To understand CAD/CAM, this article looks at the patient's journey starting with a visit to the dentist and ending with new teeth.

As digital processes permeate every industry, the demand for digital dental technology is swiftly gaining momentum and CAD/CAM (computer aided design/computer aided manufacturing) techniques are being adopted in every area by dental health professionals. In implant dentistry, digital technologies speed up the treatment process and provide greater accuracy and precision in planning, placing and restoring dental implants, leading to increased patient satisfaction through improvements in aesthetics and functioning.

Dental implants

Dental implants are artificial tooth roots made from titanium. A dentist or oral surgeon drills a hole (known as an osteotomy) directly into the bone; the implant is placed into the hole and becomes incorporated into the bone (a process known as osseointegration). The length of dental implants varies from 8–20 mm and they range in diameter from 3–6 mm. Implants can be restored with individual crowns or bridgework and essentially act as a substitute for the patient's original teeth, avoiding further bone loss through resorption.

Digital image acquisition

Imaging the patient is an essential prerequisite for successful implant treatment. X-ray images can show if the osteotomy is deep enough for the implant to osseointegrate, and crucially, if it is drilled in a location that avoids damaging sensitive anatomy.

Afroz Shaikh is Chief Imaging Scientist, Barry Chandler is Medical Applications Manager and Anthony Reynolds is Managing Director of Image Diagnostic Technology Ltd, London

Email: rar@ctscan.co.uk

Additional information required at the pre-implant planning stage includes bone quality, optimal implant sizes and angulations, and locations in three dimensions (as implant placement is essentially a 3D process).

The clinician has a range of options for imaging the patient and will often use a succession of examinations. Initial assessment is often carried out by two-dimensional imaging such as dental panoramic tomography (commonly known as orthopantomographs) or periapicals. These 2D imaging modalities deliver a low dose of radiation to the patient, can be quickly generated and provide a low-cost primary evaluation (Harris et al, 2002).

Dental panoramic tomography (DPT) relies on motion between the X-ray tube and the detector to create a panoramic image where the structures outside the focal trough are blurred and all of the structures between the X-ray tube and the image detector are superimposed on one another (*Figure 1*). Periapicals or intra-orals are X-rays of small groups of teeth taken with the detector or film inside the mouth. Although the location and height of bone can be gained from these techniques, the images are often magnified,

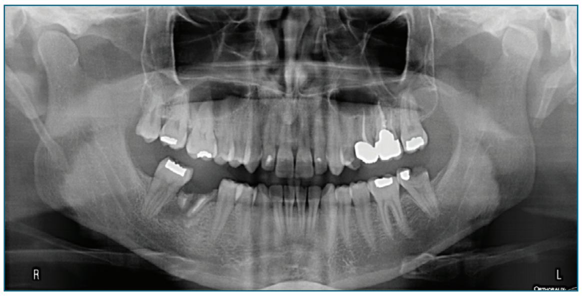

Figure 1. An example of dental panoramic tomography. This 2D image suffers from magnification and distortion and does not provide all the information required for planning dental implants. This is similar for an intra-oral X-ray.

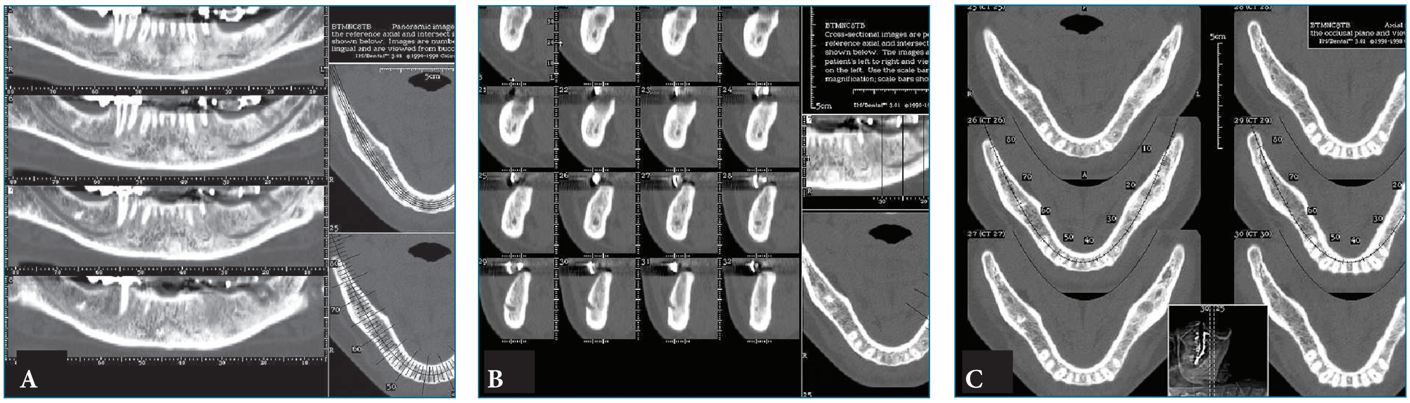

Figure 2a–c. A) Panoramic views of the mandible. B) Cross-sectional views of the mandible. C) Axial views of the mandible. These images have been reformatted from a single computed tomography (CT) scan.

distorted and do not provide the thickness of bone required for implant planning. More importantly, little or no quantitative information on bone density can be obtained. Because the data are two-dimensional, there are limitations in the image planes that can be achieved.

Computed tomography

Computed tomography (CT) has important applications in implant dentistry (Harris et al, 2002). CT scanners provide cross-sectional images generated by mathematical computation, not by blurring. CT images are acquired at right angles to the long axis of the patient; therefore, they are known as transaxial (or axial) slices. Digital processing allows a number of axial slices to be stacked up to create a three-dimensional or volumetric representation of the patient. Once a volumetric dataset has been acquired, it can be re-sliced or reformatted to produce panoramic, cross-sectional, coronal, sagittal and 3D views—all from a single data acquisition (*Figure 2a–c*).

Volumetric CT datasets have all of the features needed for computerized implant planning. CT scans present clear images of bone structure, nerves and soft tissues, thereby demonstrating pathology and indicating potential sites for implants. Spatial relationships between the teeth are clearly visible, as well as distances from sensitive structures such as nerves. Pixel intensities (grey levels) in the images represent relative radiodensity and draw their values from what is known as the Hounsfield scale (Hounsfield, 1973). Air is specified as -1000 Hounsfield Units (-1000HU) and is displayed as black; water is specified as 0HU and is displayed as grey. Dental bone is typically 200HU or more and is displayed as white. Soft tissues such as fat or muscle have densities in the range -100HU to 100HU and are displayed as various shades of grey.

Air, soft tissue, bone, teeth and even existing titanium implants can be reliably assigned to a range of values on the Hounsfield scale and this means that these different structures can be pulled out or segmented from the volume dataset and displayed as individual 3D objects. Most importantly, a quantitative assessment of bone density can be made. For example, pixel values in Hounsfield Units can be mapped directly into bone qualities D1, D2, D3 and D4 on the Misch scale (*Table 1*) (Misch, 2009).

Many different types of CT scanners are available. Medical CT scanners provide a comprehensive view of the anatomy in exquisite detail, but they are large and expensive machines which are usually confined to hospital environments. In dentistry, cone-beam computed tomography (CBCT) is superseding medical CT scanners to provide less expensive and

Table 1. Misch classification of bone density

Density	Hounsfield range	Type of bone
D1	> 1250	Dense cortical bone
D2	851–1250	Thick dense to porous cortical bone on crest and coarse trabecular bone within
D3	351–850	Thin porous cortical bone on crest and fine trabecular bone within
D4	150–350	Fine trabecular bone

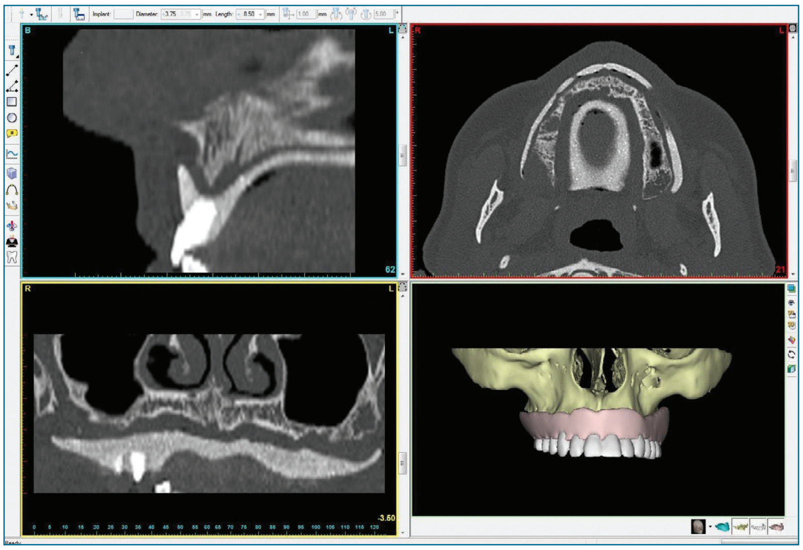

Figure 3. Edentulous patient wearing a radio-opaque scanning stent. The base of the stent has been made from a 10% mixture of barium sulphate and acrylic; the teeth contain 15% barium sulphate. The mucosa is clearly outlined as the grey area between the radio-opaque stent and the patient's bone.

lower dose alternatives (Guerrero et al, 2006). CBCT scanners use a cone-shaped beam of X-rays radiating from the X-ray source, so that an entire volume is imaged with a single rotation about the patient's head (whereas with medical CT scanners, multiple rotations are required).

From imaging to restoration

To understand where automation can be introduced and CAD/CAM can play a role, it is useful to look at the patient's journey starting with a visit to the dentist and ending with new teeth. While there are compelling biological reasons why some stages in the process may take several months to complete, other steps can be automated and in principle speeded up.

Taking a digital impression

One of the first steps in planning dental implants is taking an impression of the patient's teeth and gums. The impression material is placed in the patient's mouth and, when hardened, is sent to the dental laboratory where a plaster cast or study model is poured. The plaster cast is used to produce a waxup or a provisional diagnostic prosthesis demonstrating the desired restoration. The diagnostic prosthesis can be tried in the patient's mouth and tested for aesthetic considerations and also speech, chewing and other functional requirements.

Impressions are traditionally taken by pouring a material, such as alginate or silicone, into an impression tray and bringing it into close physical contact with the patient's teeth and gums. However, this approach is time-consuming, uncomfortable for the patient and the results are operator-specific and not always very accurate. For CAD/CAM processing, the impression must be optically scanned at the dental lab (or a plaster cast poured, sectioned and then scanned).

Recently, intra-oral devices have been developed that use optical scanning to acquire a three-dimensional digital representation of the inside of the patient's mouth. There is no direct contact with the patient's teeth and gums (hence, less distortion) and the data can be transmitted electronically to the dental lab. This technology has been pioneered by companies such as Sirona (the CEREC system), CADENT (iTero), and 3M/Espe (Lava™ Chairside Oral Scanner). At least one manufacturer (Sirona) has produced software to combine the digital impression with CBCT images of the same patient.

Making a radiographic scanning stent

Once the diagnostic prosthesis has been approved by patient and clinician, a radiographic scanning stent can be constructed. This is a plastic stent worn in the patient's mouth at the time of the CT scan, incorporating radio-opaque teeth or markers designed to show up clearly in the CT images. A mixture of barium sulphate and acrylic can be used for the markers, as acrylic on its own will not be visible. Sometimes the entire base of the stent is constructed from acrylic mixed with 10% barium sulphate by weight, while the teeth or markers contain 15% barium sulphate by weight so that they can be segmented separately (*Figure 3*). Such a stent is useful to delineate the mucosa (the grey area between the radio-opaque scanning stent and the bone, in *Figure 3*) and is a prerequisite for one of the techniques used to construct a mucosa-supported surgical drill guide for edentulous patients, as discussed below.

Finding an imaging centre

Finding an imaging centre that is knowledgeable and experienced in taking dental CT scans has always been a challenge. Medical CT scanners are usually located in hospitals where they are used for general imaging work, and the operators may require special training in positioning the patient for dental imaging. Moreover, the scanner settings must be carefully selected to keep the radiation dose 'as low as reasonably practicable' (ALARP).

Recently, many imaging centres and private dental

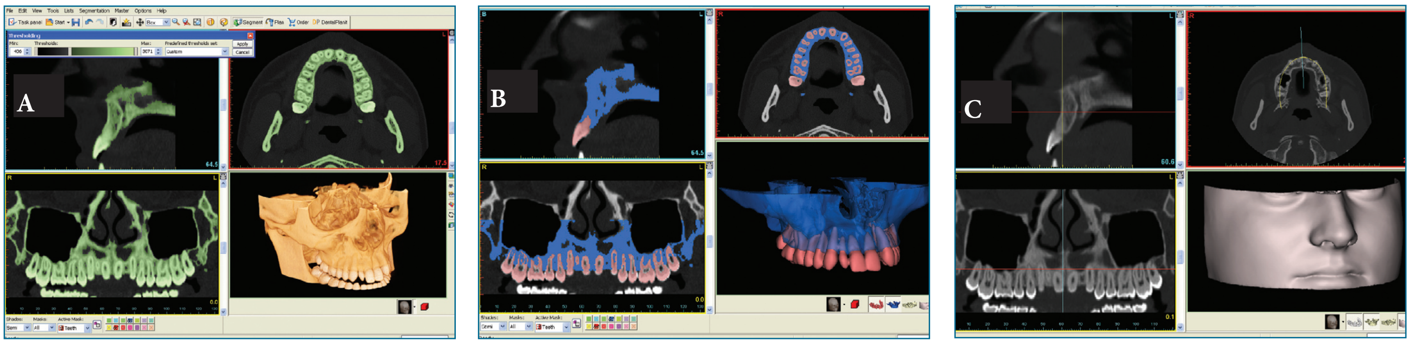

Figure 4a–c. A) SimPlant automatically generates panoramic, cross-sectional, and volume-rendered 3D views from axial slices. B) The segmentation process separates particular anatomy based on Hounsfield Units. C) The final result showing the finished 3D complete with the skin surface.

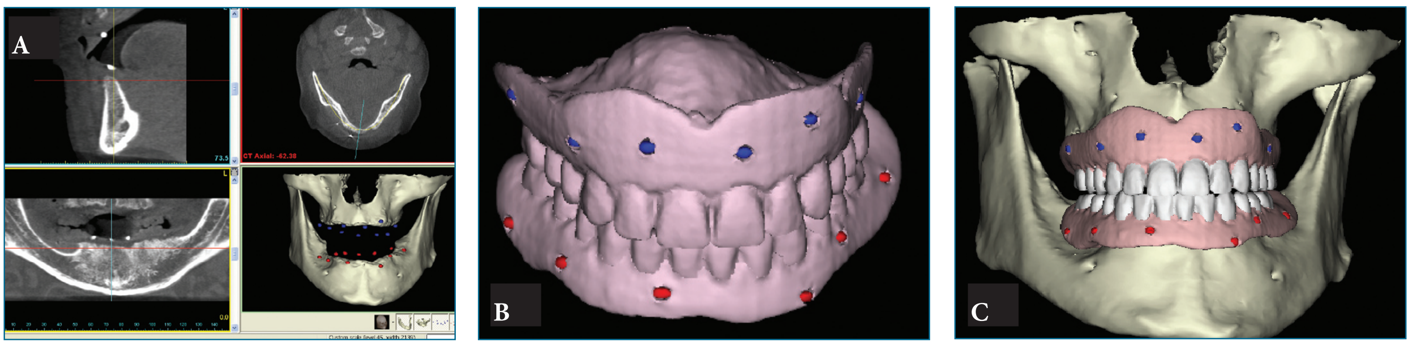

Figure 5a–c. Dual scan technique. A) Patient scanned wearing a plastic stent with radio-opaque markers. B) The same plastic stent scanned separately, in air. C) Data processing centre combines the two datasets making use of the common markers.

practices have installed CBCT scanners and a number of websites are available to assist in finding a suitable imaging centre. IDT operates a website which lists selected imaging centres across the UK and Ireland, and Materialise Dental is introducing a service known as Dental Planit which will assist in locating imaging centres worldwide.

IDT's homepage is located at www.ctscan.co.uk and the search engine is based on an active map. The user can search by postcode or keywords and view a number of imaging centres close to their location. After identifying themselves as a dental professional, users can request a dental CT scan and specify the data processing requirements, all online.

The role of the data processing service

The axial images produced by a CT scanner are rarely in a format directly suitable for planning dental implants. The standard output from medical imaging equipment is DICOM (Digital Image COMmunication in medicine). The role of the data processing service is to make new images from old, converting DICOM datasets into panoramic and cross-sectional views as shown in *Figure 2*. However, a good processing service can do much more than that. Some additional services are:

- Segmenting the data and removing artefacts to make 3D views
- Converting the data for input into leading software packages such as SimPlant, Nobel Guide, Med3D, VIP, In Vivo, Keystone, or iDent
- Registering two datasets (e.g. the patient's data with the scanning stent or plaster cast)
- Obtaining a radiologist's report or an expert implantologist's treatment plan.

Reformatting the data

Once the data have been acquired from the CT machine, they must be reformatted to create views more directly useful to the dental practitioner. SimPlant (produced by Materialise Dental NV) is one of the most widely used software packages for dental implant planning. Data processing services such as IDT are able to receive DICOM data from any CT or CBCT scanner and convert it into SimPlant-compatible datasets.

The process of creating 3D objects out of 2D images is termed segmentation (*Figure 4a–c*). Each 3D object is created from a selection of pixels in the 2D images known as a mask.

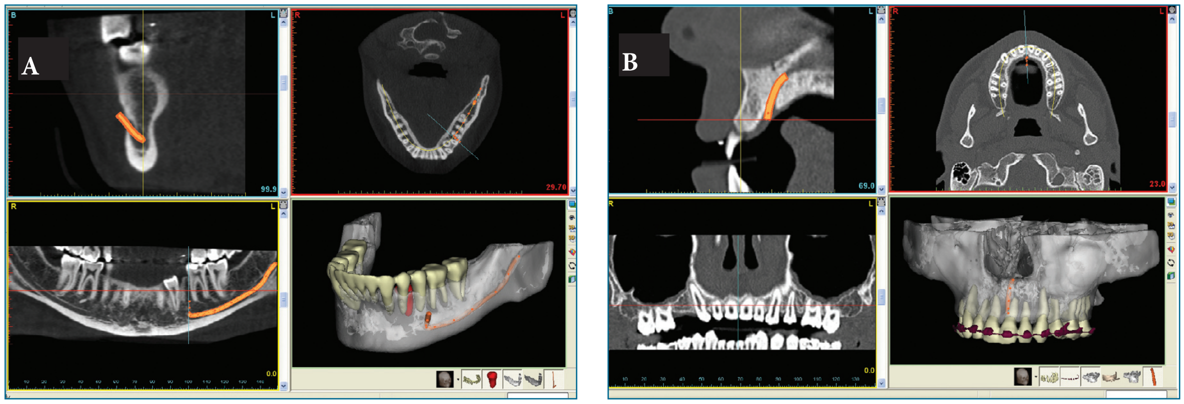

Figure 6a–b. A) CBCT images of a mandible (taken on an i-CAT). The inferior alveolar nerve can be clearly seen on the patient's right in the panoramic view. The nerve has been drawn in as seen in orange on the patient's left. An embedded tooth can be seen in the 3D image (shown in red). B) CT images of a maxilla (taken on a medical CT scanner). The incisive foramen has been drawn in orange. The maroon object in the 3D image shows the patient is wearing orthodontic braces.

Registration of two datasets

Data processing centres can also perform advanced techniques such as registering two datasets. If the patient was scanned wearing a plastic denture instead of a radio-opaque stent, the denture can be scanned separately and registered with the patient scan – provided it contains radio-opaque markers which can be visualised in both datasets (*Figure 5a–c*).

The CAD in implant dentistry – digital dental planning

Once the data have been reformatted, the clinician can pinpoint areas of interest and use sophisticated software tools to place virtual implants on the computer screen. Sensitive anatomy such as the inferior alveolar nerve can be identified and drawn in (*Figure 6–b*). This is crucial since damage to the nerve can result in debilitating facial paraesthesia. The incisive foramen and the maxillary sinuses should also be avoided during surgery. Measurements from CT scans can be carried out to sub-millimetre accuracy, thus providing great confidence that implant placement will proceed safely.

Placing virtual implants

SimPlant allows the clinician to place virtual implants directly on the computer screen. The implants can be placed in any plane, re-positioned and rotated to any angle. Virtual implants can automatically be placed, uniformly spaced and parallel to each other, and the spacing between implants and neighbouring teeth can be controlled. A plethora of implant and abutment shapes and sizes is available in the built-in implant library, thus the clinician can select the most appropriate fixtures for the proposed treatment plan.

The CAM in implant dentistry – from the digital plan to surgery

An accurate pre-surgical treatment plan can be a valuable functional and aesthetic tool for the dental implantologist. It is however only half of the story of computer-assisted dentistry. The CAM in dental implants takes the form of surgical drill guides and computer-fabricated restorations. Using the computerized treatment plan the clinician has the opportunity to order a surgical drill guide which is manufactured under computer control with drilling cylinders corresponding to the size and location of the virtual implants placed within the software. The metal cylinders constrain the dentist's drill to the exact position dictated by the computerized treatment plan.

Surgical drill guides

The drill guide is made from biocompatible acrylic resin and can therefore be placed in the patient's mouth during the surgical procedure. The guides are placed in a unique position on the patient's teeth, mucosa or bone. Drill guides made using CAD/CAM techniques are sufficiently accurate that, after placing the implants, the abutments and prosthetic teeth or bridgework can be placed in position and the patient leaves with teeth—sometimes the same day.

Classic SurgiGuides® (Materialise Dental NV) consist of a set of three surgical guides to aid in the correct preparation of the osteotomy sites. The three guides are used in succession and are called pilot, intermediate and final to correspond to the respective drills. Classic SurgiGuides do not physically stop the drill at the required depth; however, each SurgiGuide has the top of its drill cylinders exactly 5 mm above the drilling surface. The calculated drill depths must be increased by 5 mm from the planning stage and armed with this information, the dentist is able to manually stop drilling at the required depth.

More complex surgical drill guides such as SAFE SurgiGuides® (Materialise Dental NV) and NobelGuide™ (Nobel Biocare) are able to regulate the depth of the drill as well as its position and angulation.

Once the design of the guide is complete the guide is manufactured using stereolithography, which is a one of a number of rapid prototyping (RP) techniques. Stereolithography is used extensively in the manufacturing industry to build physical models from computer data. A highly accurate laser directs ultraviolet (UV) radiation onto a bath of liquid acrylic resin, in which a flat plate, known as an elevator, has been placed just underneath the surface. This plate creates a barrier, as the laser is not able to penetrate past it; therefore, only a thin layer of the model is made at a time. When the laser interacts with the liquid, the resin is cured and hardens. The elevator is then lowered and the next layer of the model is created. Models of the mandible, maxillofacial region or the entire skull can be produced using this technique.

Computer manufactured restorations

The final stage of implantology is restorative; this involves placing crowns, bridges or veneers to give the patient their new teeth. Previously, this would require a series of dental appointments, taking dental impressions, and the fabrication of the restoration by a dental laboratory. Today, CAD/CAM techniques allow the clinician to custom-make restorations and put them in place in a single appointment using systems such as CEREC (Sirona) or D4D (D4D Technologies plc).

CEREC stands for 'CEramic REConstruction' and the original system was designed for chairside fabrication of simple restorations such as crowns. The system incorporates a stereo camera, computer and milling machine all designed to fit within the dentist's surgery. Using the special camera, the dentist takes a digital impression of one or more prepared teeth, which is relayed to a computer where the crown can be designed using 3D CAD technology. The CAM part then takes over and creates the crown on a milling machine in the dentist's office. After approximately 15–30 minutes the dentist bonds the restoration to the surface of the prepared tooth and the patient goes home with the new crown in place. For more complicated restorations (perhaps involving implants), digital impressions can be sent to a dental laboratory to perform the necessary work.

Conclusions

CAD/CAM technologies are being firmly grounded in the dental implant process. CBCT scanners provide 3D dental imaging at a low radiation dose and allow for the visualization of suitable implant sites. The CAD of dental implant planning offers the ability to design a proposed treatment plan avoiding sensitive regions, assuring the clinician that these sites will not be compromised. The CAM of surgical guides controls implant positions, trajectory, depth and distribution at the time of surgery. Computer manufactured restorations provide the digital seal to the whole procedure. CAD/CAM technology in dental implants is driving faster, more predictable, less invasive routes for treatment and better aesthetic and functional outcomes for both clinician and patient. DN

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Conflict of interest

Image Diagnostic Technology Ltd provides a data processing service and our sister company, IDT Dental Products Ltd, sells and supports i-CAT CBCT Scanners, SimPlant software and SurgiGuide drill guides in the UK and Ireland.

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KEY POINTS

- **The demand for digital dental technology is swiftly gaining momentum.**
- **Computer aided design/computer aided manufacturing techniques are being adopted in every area by dental health professionals.**
- **Digital technologies speed up the treatment process and provide greater accuracy and precision.**