Microtechnologies in implant and restorative dentistry: a stroll through a digital dental landscape

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Abstract: This is an explanatory article introducing the combination of various technologies used in implant and restorative dentistry. The aim of the article is to provide an overview of some of the techniques supporting the restorative treatment plan at various stages to provide contemporary, state-of-the-art bridgework based on dental implants. It is a discussion of the way existing technologies used in fields of engineering and medicine are brought together to form a complete process.

Keywords: implant dentistry, digital dentistry, restorations, virtual surgical planning, guided surgery, cone beam computed tomography, rapid prototype, rapid manufacture, anatomical models, drill guide, computer-aided design

1 INTRODUCTION

Dental implants are titanium fixtures that are screwed into the jawbone to support prosthetic teeth, in the form of dental crowns or bridgework. Conventional implant treatment involves making an incision along the jaw and stripping back the gum and oral mucosa to 'raise a flap' and expose the underlying bone (Fig. 1). Sites are then prepared in the exposed jaw bone with twist drills. Titanium screw-form fixtures are installed in the jaw and with the passage of time form an intimate union with the living bone, so called 'osseointegration' [**1**]. Such restorations have proved reliable over extensive periods of time and have become commonplace [**2**, **3**]. Similar technology is used to retain extra-oral prostheses in facial reconstruction [**4**].

Digital technology is changing every aspect of our personal and professional lives. In the world of implant dentistry there is a convergence of scanning, manufacturing, and surgical technologies that has made possible faster, more predictable, and less invasive treatment for patients requiring implant procedures. Using the example of a patient missing all teeth, this article illustrates the array of technological processes that may be brought to bear to facilitate preparation and planning, less invasive and more efficient surgical treatment, and laboratory technique.

It has become common to use computer-aided design (CAD) processes to plan implant surgery, transfer the plan to the patient, and finally design the dental prostheses or bridge, using rapid prototyping (RP) or rapid manufacturing (RM) techniques to manufacture the definitive restoration. Although seemingly very different, the various machines and software solutions available in dentistry have this in common: they make it possible to move from the physical patient to a virtual on-screen environment, and then back to the physical, using scanning, CAD, and RP/RM (known as *digital dentistry*). A common thread in all these treatment modalities is the need for a digital, three-dimensional (3D) representation of the patient, a *substrate* for virtual planning, surgery, and manufacturing.

In the past, 3D patient image data for surgical planning in implant dentistry were gathered using computed tomography (CT) examinations of the

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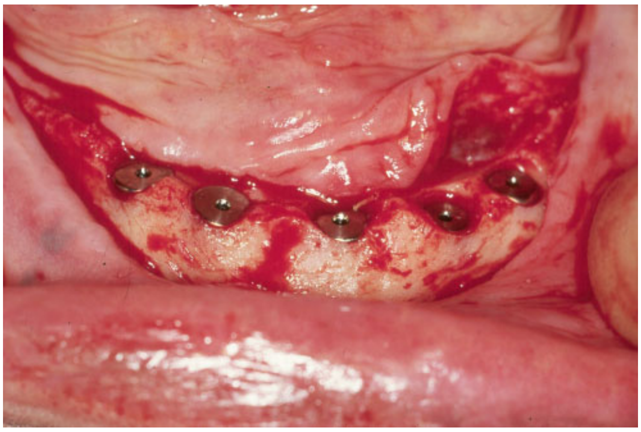


Fig. 1 Conventional implant surgery with five implants in place. Note the extensive incision revealing the mandibular jawbone

jaws. However, CT is a high X-ray dose examination, and CT scanners are large and expensive, and usually only found in hospitals. A new type of scanner, the cone beam computed tomography (CBCT) scanner [**5**] (Fig. 2), has dramatically changed access to low-dose [**6**], precise, 3D volumetric scan data. Also, similar advances in the scanning of freeform objects have revolutionized the processes that usually take place in the dental laboratory, enabling digital design of prostheses and finally manufacture using RP/RM technologies.

RP technology particularly lends itself to the production of dental prostheses, as each unit is unique, made to an individual prescription for a particular patient, hence the term *rapid manufacturing* may be more specifically applied. RM technology has evolved in this same timeframe to enable the predictable production of dental prostheses or appliances in a wide variety of dental materials, including titanium [**7**], zirconium [**8**], cobalt chrome, and resin.

2 DISCUSSION OF TECHNOLOGIES

2.1 Cone beam computed tomography (CBCT)

The introduction of CBCT technology means that 3D imaging is likely to become routine for any patient requiring complex diagnostic or surgical procedures where hard tissues are involved. Dental CBCT machines are much more compact than hospital CT scanners (Fig. 2). Most dental CBCT scanners are vertical, so the patient is seated or standing rather than supine. Whereas conventional CT scanners acquire 'data' incrementally, CBCT scanners use a very different approach. Remarkably, using back-projection tomography, the whole volume of data is 'acquired' in the course of a single rotation of the X-ray source, conical X-ray beam, and opposing sensor around the patient's jaw(s).

CBCT apparatus uses large-area amorphous silicone solid-state sensors rather than image intensifiers. These receptors have the advantage that the data are directly acquired, contributing to a significant reduction in X-ray exposure, to an order of magnitude less than conventional CT and to a level

Fig. 2 A cone beam CT scanner with the patient positioned for a scan of the jaws

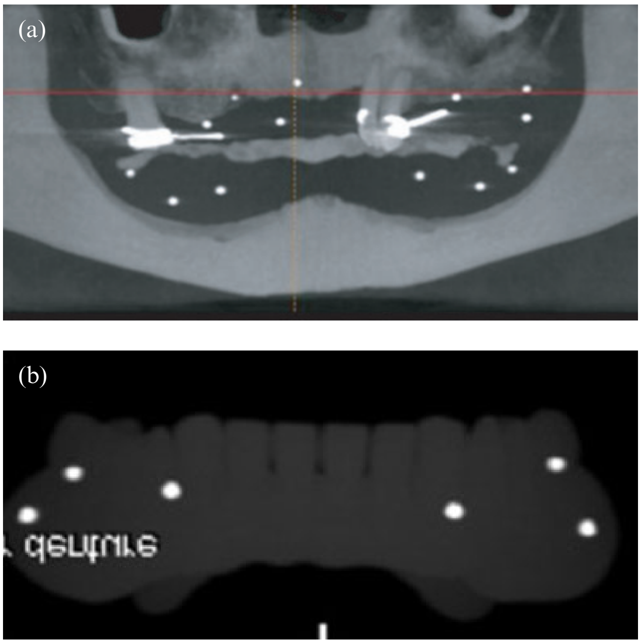


Fig. 3 (a) A 'panoramic' image generated by a CBCT scan of the patient scanned with upper and lower dentures in place. Note that the radio-opaque circular markers are visible, although the dentures are not. (b) A 'panoramic' image generated by a CBCT scan of the denture with radio-opaque markers in place

that is still higher but closer to that of conventional dental imaging techniques.

2.2 CBCT software and compatibility

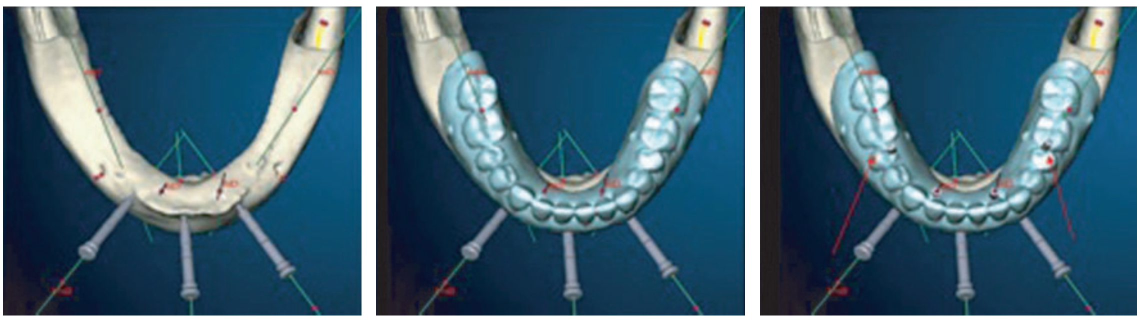
The mechanical construction of the CBCT apparatus is relatively simple, but the associated software, which allows the huge volume of data acquired in the course of a scan to be reconstructed, is highly sophisticated. This software is able to export the data in DICOM (Digital Imaging and Communications in Medicine) format. This is the standard for viewing and distributing any medical image and allows data to be imported into multiple software platforms, including CAD software for modelling, and interaction in a virtual environment [**9–11**].

2.3 The NobelGuide^{TM} concept

'Guided surgery' [**10–13**] has become easily accessible using the NobelGuide^{TM} protocol (Nobel Biocare, Gothenburg, Sweden). This protocol calls for the patient's denture to be marked with small radio-opaque fiducial markers and scanned separately 'in air', and for the patient to be scanned with this marked denture in place (Figs 3(a) and (b)). As the denture is designed to fit soft tissue (gums), the protocol enables the associated software to coregister the radio-opaque markers from each scan to replicate the relationship between the denture and jaws of the patient in an on-screen environment. This works as a convenient way to develop separate virtual models of the patient's jaws and the form and position of the prosthetic teeth.

2.4 Virtual surgery

Having created a virtual model of the patient's jaw (Fig. 4(a)), dedicated implant planning CAD software, which contains a 'library' of implant types, may be used to carry out virtual implant surgery in this simulated environment. The position of the implants may then be planned in relation to the intended position of the final planned prosthetic result, as judged with respect to the patient's existing removable denture (Figs 4(b) and (c)). A specification for a constraining drill guide with the same basic geometry as the original denture, which fits over the jaw to guide drills into precisely the correct



(a) (b) (c)

Fig. 4 Implants planned in the virtual CAD environment (NobelGuide^{TM}; Nobel Biocare, Gothenburg, Sweden) positions, is then generated by the software and exported as an STL file for RM.

2.5 Interfacing with the patient: 3D printing; a drill guide and RP anatomical models

There are many RM machines available for the production of robust physical objects from CAD data. This process is becoming increasingly accessible, allowing the accurate 'printing' of physical structures from scanned objects.

Stereolithography apparatus (SLA) uses a scanning laser beam selectively to polymerize layers of photopolymer to produce a robust resin structure. This process may also be used to produce high-resolution physical anatomical models directly from scan data. The rapid prototype anatomical model (RPAM) may be thought of as a tangible 'study model' for surgical planning. RPAMs may be physically prepared as a 'dry run' and facilitate communication among members of the dental team, including the technician and patient, without the need for a computer or specific software. This approach is finding a strong foothold in maxillofacial and craniofacial surgery, where it has become the norm for planning complex surgery [**14**] or forming [**15**, **16**] components of the reconstruction. However, in this case, an SLA rigidly constraining drill guide is printed to the CAD specification. The drill guide has the same fitting geometry and fits over the jaw in the same way as the patient's original full denture (Figs 5(a) and (b)). The implant positions that have been planned in the virtual environment are translated into apertures in the drill guide that house stainless steel guiding sleeves.

2.6 Guided surgery

Rather than cutting into the tissues as for conventional implant surgery, implant site preparation takes place using twist drills and associated instrumentation designed to pass through the guiding sleeves. Implants are screwed into place through the drill guide using mounts that constrain the vertical placement of the fixture to a position defined by the guide, thus precisely following the virtual implant plan (Fig. 6(a)). Surgery is minimally invasive, and consequently there is little bleeding, swelling, or bruising post-operatively (Fig. 6(b)), and may be

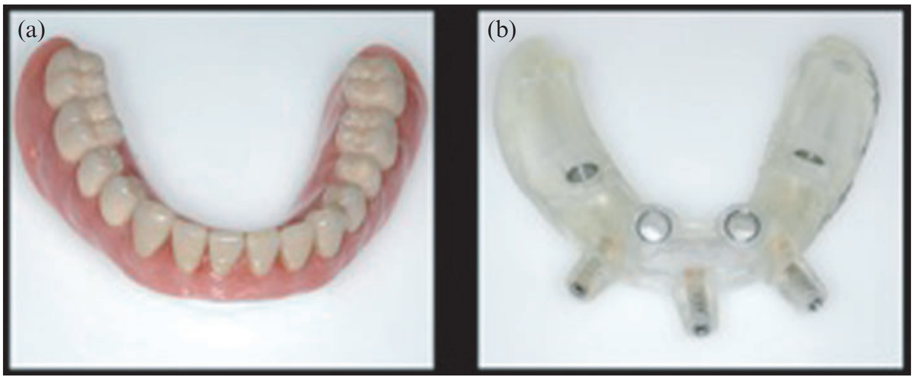


Fig. 5 The original lower removable denture (a) acts as a template for the surgical planning, and (b) dictates the fitting geometry of the drill guide

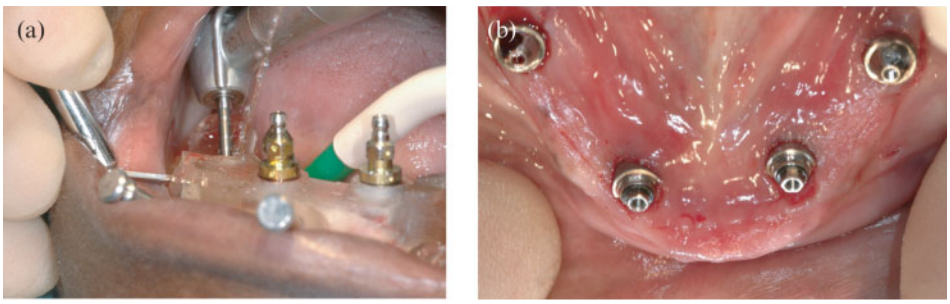


Fig. 6 (a) The drill guide anchored in position in the mouth. Site preparation continues, but two implants have been placed through the guide. (b) The completed surgery with all implants in place – note the lack of bleeding and minimally invasive treatment

compared with conventionally placed implants in Fig. 1. The surgical procedure is highly accurate, as various studies comparing planned with achieved results have shown [**17**, **18**].

2.7 Dental model scanning and RM prosthesis production

Having accurately installed implants into preplanned positions, the next stage is to proceed with fabrication of the dental prosthesis or 'bridgework'. When producing implant bridgework, it is important for the prosthesis to fit the implant supports accurately, aiming to minimize any 'gap' between prosthesis and supporting tooth or implant, typically to less than 50 μm. In the past this was achieved using traditional lost-wax and investment casting procedures to construct metal bridge superstructures, onto which resin or porcelain aesthetic coverings would be bonded. This form of casting technology has been available since before the days of the Aztecs and in principle has changed little since that time.

Recently there has been a dramatic uptake of digital technologies in the dental laboratory. Once again the first step is to input patient data into a virtual environment for digital interaction. CBCT is ideal for visualizing anatomical structures, but lacks the 'resolution' needed for definitive prosthesis manufacture. Currently the need for high precision makes it necessary to record an impression of the implants in place. A common 'digital' approach is to scan the poured plaster model of the jaw using a contact scanner [**19**] to develop a virtual model of the planned teeth, implant, and jaw.

More recently, various optical techniques, including photogrammetry [**20**] and conoscopic holography (Fig. 7(a)), have been used to scan models, and now even the impression itself, using a non-contact approach enabling scanning of steep angles, difficult geometries, and a wide variety of materials with precision. The scan data are converted into a 3D file and visualized on-screen (Fig. 7(b)); the detailed contour of the structures may be developed further in the CAD software, using keyboard, mouse, or even more intuitive haptic hardware devices (Fig. 8), to design bespoke metal or ceramic structures such as thin zirconium or cobalt chrome bridge superstructures [**21**].

Computer numeric controlled (CNC) milling is widely used to produce prostheses in pure titanium with a great deal of accuracy [**22**], and this is the technology used in the case of the patient in Figs 9a to c. Similar CNC technology is used to mill

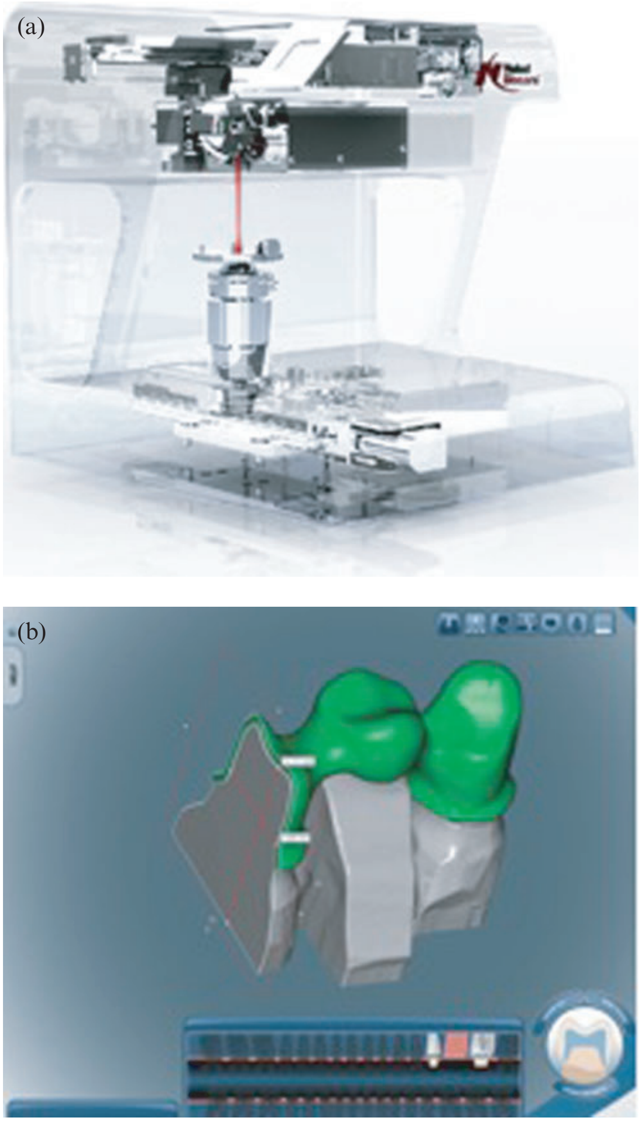


Fig. 7 (a) A recently introduced scanner that uses conoscopic holography to scan dental models and impressions (NobelProcera^{TM}; Nobel Biocare, Gothengurg, Sweden). (b) Virtually 'editing' the scanned prosthesis in the CAD 3D environment

structures in alumina or zirconia in a 'green' presintered state [**23**, **24**], although the long-term reliability of larger ceramic structures is yet to be established [**25**]. RM technology has the capacity directly to produce structures in a wide variety of materials, including resins, ceramics, metals, and alloys. With the exception of milled titanium (Figs 9a to d), there are few or no clinical data on the use of RM of metal or alloy dental crown or bridge components. There are also few or no scientific data available on the use of layered building techniques such as selective laser sintering (SLS) or direct metal laser sintering (DMLS), although systems employing

Fig. 8 A haptic device (SensAble Technologies, Woburn, Massachusetts) for use in the digital dental laboratory; intuitive manipulation of the on-screen object with proprioceptive feedback

this technology are commercially available and in use. Even the lost wax process has evolved such that the sacrificial pattern – the wax portion that would be burnt out in a traditional casting process – has been replaced with materials laid down in RP processes [**26**].

3 SUMMARY AND CONCLUSION

This article has discussed a range of scanning, planning, manufacturing, and clinical techniques with associated hardware and software currently used in implant and restorative dentistry. It has also outlined the benefits of CAD and RM processes in reducing the duration of treatment, minimizing the invasive nature of surgery, and increasing the accuracy and reliance upon manual processes. The type of collaboration described in this article 'bridges the gap' between radiologists, clinicians, technicians, engineers, material scientists and software developers. Use of these digital technologies is becoming increasingly prevalent, both in dentistry and other medical specialties. An understanding of the technological processes is invaluable to the

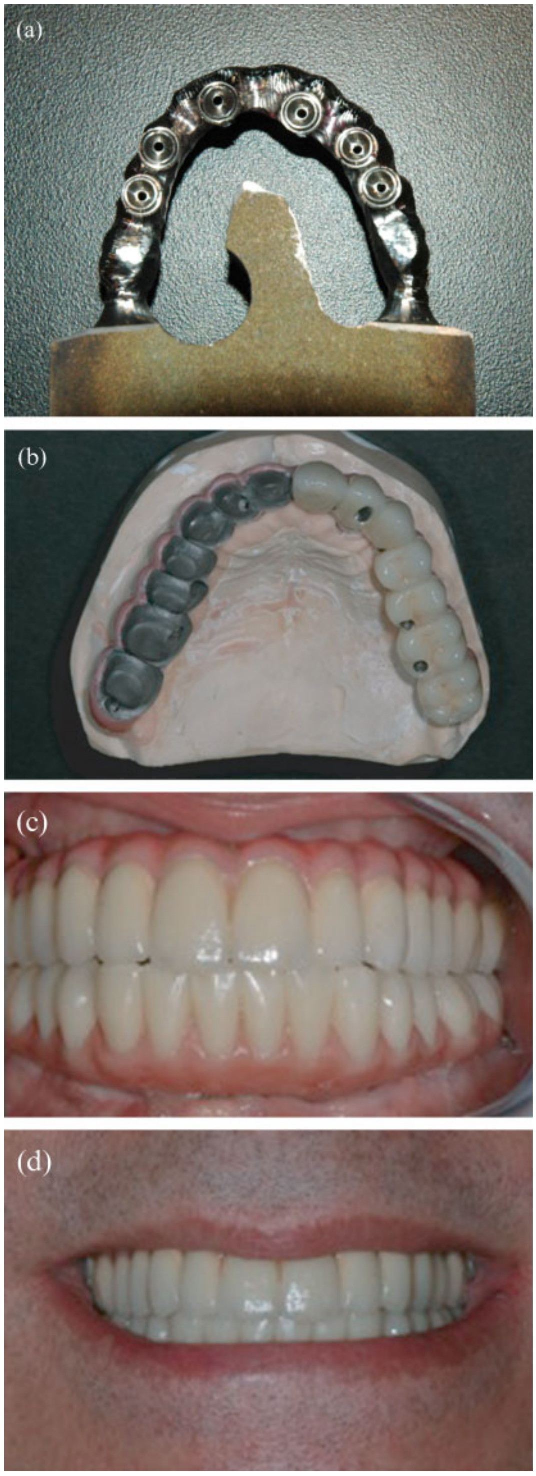


Fig. 9 (a) A partially milled titanium bridge framework that will be supported by dental implants. (b) Titanium bridge framework prepared to receive individual ceramic crowns. (c), (d) Clinical photographs of completed implant bridges in place in both jaws

clinician, while an understanding of the clinical needs is similarly invaluable to the engineer.

4 THE FUTURE

What works well in the research laboratory or in the hands of specialists may be less predictable in less experienced hands than existing artisan technologies. Innovation is commercially led, and there has been remarkably little scientific evaluation of CAD or RM technologies and treatments in particular, most importantly in the general dental practice environment. There is currently little detailed scientific literature available on many of these remarkable but proprietary technologies. The accuracy, predictability, and durability of CAD technologies and RM artefacts need careful study. However, dentistry is exceptionally fertile territory for engineers working in radiology, medical physics, surface metrology, computer-aided design, rapid manufacturing, and all the various materials associated with these processes. A better understanding of the processes involved will hopefully lead to more productive collaboration between clinicians and scientists working in these important fields.

Returning to the specific type of treatment described here, it is clear that soon, with the use of emerging technologies, it will be possible to move from an on-screen surgical plan to a finished implant prosthesis without impressions, without flaps, and with total accuracy.

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