high contrast

errors

resolution

data-transfer

infra-red control

technology

accuracy

New concepts in computer-guided implantology

Part II: Error analysis and accuracy verification

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_Abstract

In recent years, there has been a growing interest in guided implantology. A digital work-up is certainly of great benefit for clinicians to better understand their patients' bone morphology and density and consequently to plan implant positions correctly, and to have their hands guided during implant placement by means of a surgical guide. There are many systems on the market today and many researchers have studied post-operative CT scans and planning scans by means of superimposition, in seeking to understand the secret to achieving perfect correspondence and the best system, but this perfect accuracy has not yet been found and there appears to be a mismatch between planning and the actual implant position.

I have developed a device (Dental Implant Positioning System, International PCT IT 2009 000192, WO 2010/125593 A1; patent pending) that respects the implant's spiral movement in accordance with mathematical criteria. The same criteria are also important in theorising limits and achieving accuracy using computer-guided implantology.

_Introduction: Passive systems and the limits of the human visual, auditory and spatial resolution

Is it possible, using one technique, among the many on the market, to create repeatable results in terms of a final prosthesis? How many of the presently marketed systems in guided implantology really are passive? Do passive infra-red systems really facilitate repeatability?

Human visual resolution limits do not allow for accuracy: eye, ear and fine hand movements have not yet crossed this threshold. Human spatial resolution can be evaluated with reference to the modulation transfer function (MTF). This is also a good

means of evaluating the optical properties of CT scans. Spatial frequency has been widely studied and it is now generally accepted that line pairs (black and white) can be perceived up to a tenth of a millimetre (human visual acuity). The same is true for hearing (in hertz) and hand movements (we cannot control a movement beyond 0.1 mm).

A passive device therefore appears necessary to ensure that the same implant position can be reproduced repeatedly and independently of the operator within the threshold defined above. This fulfils my definition of "passivity".

_The limitations of infra-red control systems

This last point also means that infra-red control systems are excluded by definition, since their accuracy is operator dependent. Apart from spatial resolution limits, this kind of technology is affected by time-delay problems, partially due to the machine itself and partly due to the temporal resolution limits of the operator (eye, ear, hand). Therefore, infra-red control should not be considered passive. These systems are equipped with a virtual smooth sleeve and are operator dependent. Furthermore, they can be monitor or mouse guided, when the handpiece is transformed into a computer mouse. Ironically, we tend to consider the surgical tutoring toy a passive tutoring system only because it is provided with sensors along its holes (Figs. 16a & b), but not because of its functionality.

It is my opinion therefore that an entirely passive device, in which all necessary information is included, is superior to semi-active devices. Furthermore, passive devices should be easy to handle and intuitive to use, and their design should not allow any freedom for the operator (the operator has already decided upon the location of the implant through planning and the surgical guide).

_Accuracy verification

Many studies on accuracy verification have been conducted. In these, scientists have sought to determine and measure accuracy by means of comparing the planning data and data acquired post-operatively. Their aim is to evaluate which of the marketed systems delivers the most accurate results.
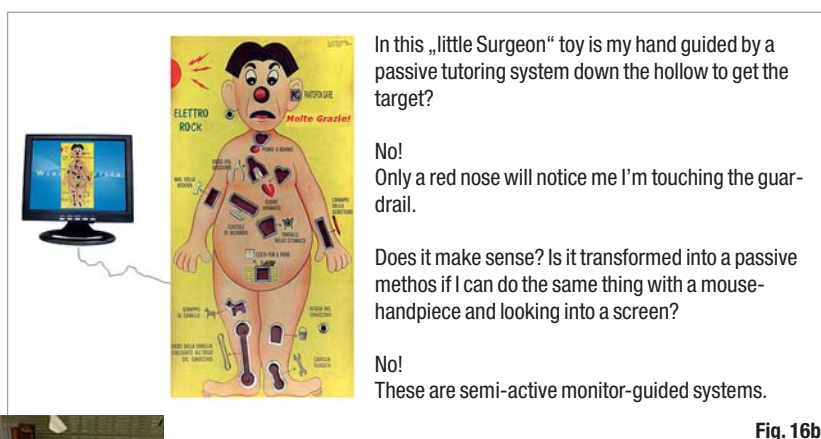

In this „little Surgeon" toy is my hand guided by a passive tutoring system down the hollow to get the target?

No!
Only a red nose will notice me I'm touching the guardrail.

Does it make sense? Is it transformed into a passive methos if I can do the same thing with a mouse-handpiece and looking into a screen?

No!
These are semi-active monitor-guided systems.

Fig. 16b

In Part I, I discussed smooth-sleeve-related inaccuracy from a theoretical perspective. We must also realise that a reliable evaluation of accuracy requires measuring device. Is CT a reliable technique? Is superimposition a good means of evaluating accuracy in implant placement? Does it consider all the parameters that define the implant position (including the hex)? To prove validity and measurement accuracy, repeatability should be considered as important as its underlying mathematics.

Even if a perfect superimposition has been carried out, CT artefacts and the voxel size (which is 0.125 mm at the best) not being an issue, and considering the CT scan as a continuum, its results appear to be invalid information. Scanners, like any

Fig. 16a_The surgical tutoring toy.
Fig. 16b_Operator-dependent super technological system.

Fig. 17a–b_CT scan MTF limits.
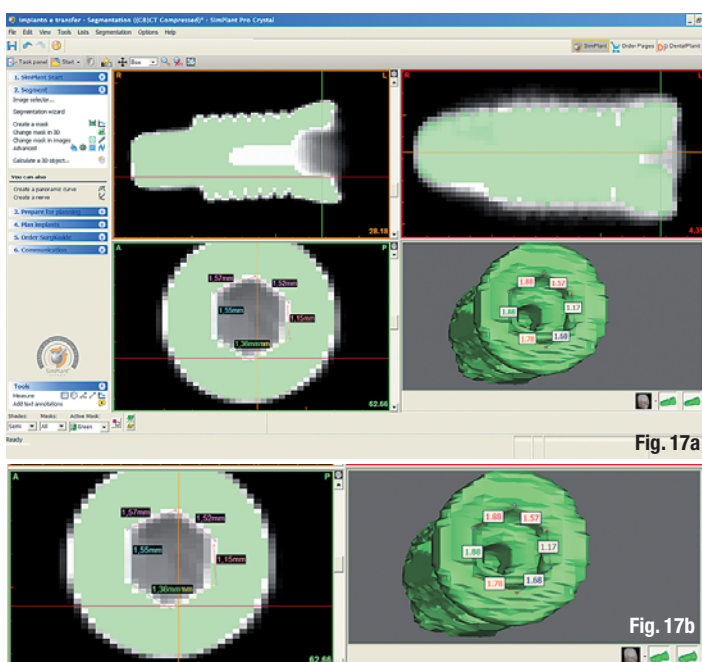

Fig. 17a

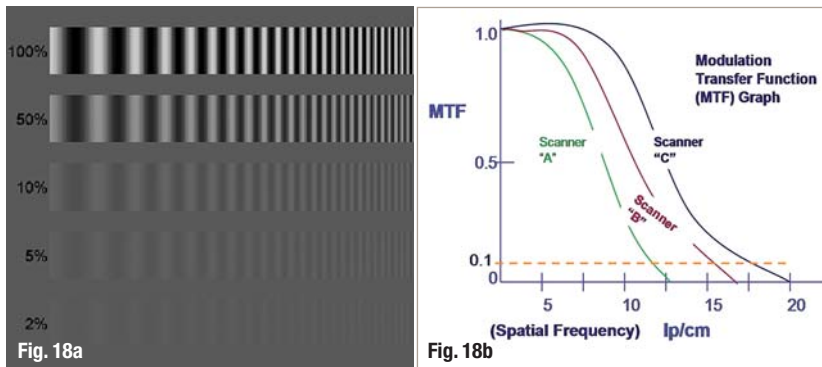
Fig. 17b

Fig. 18a

Fig. 18b

Fig. 18a–e_MTF concept.

other optical system, have optical limits and owing to CT's MTF and intrinsic limits, CT scans can be considered low-resolution 3-D images. They also achieve spatial resolution levels far from those needed in our field to ascertain placement precision. Consequently, statistical inferences based on superimposition cannot be said to deliver valid proof.

_High–contrast spatial resolution

I scanned an implant using the latest NewTom CBCT (CB3D VG-I MARK 3), and viewed the scan using SimPlant Crystal (Materialise Dental) to verify the resolution and the precision of the measurement. The best I was able to achieve was 0.1 mm. This means that a real measurement of 1.43 mm could be achieved on CT within 1.33 and 1.53 mm, and 0.3 mm is the possible measurement error (Fig. 17a). The same difficulties also arise with MSCT scans (Fig. 17b).
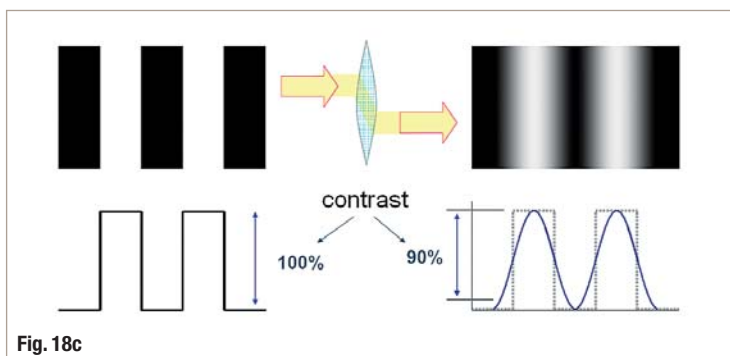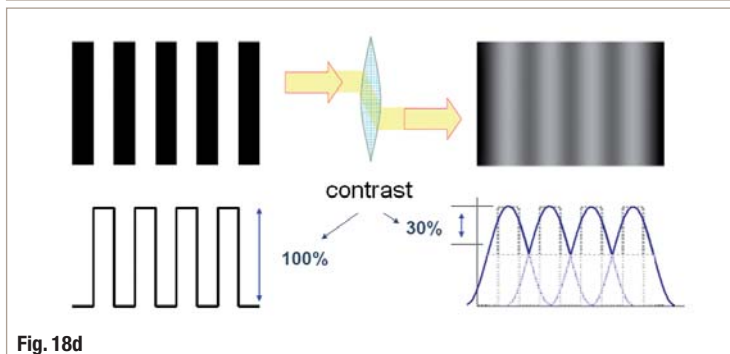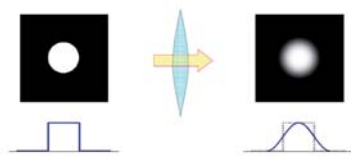

Fig. 18c

Fig. 18d

Spatial frequency is evaluated by means of MTF, the ratio between the output and the input signal, with one describing an ideal system with no loss of information at the output. MTF defines limiting resolution, which describes the ability of a system to perceive two objects as distinct. At high frequencies, that is a high number of line pairs per mm (lppm), MTF will approach zero (Figs. 18a & b). When taking MTF into account, we must evaluate a CT scan according to its optical performance. When the frequency is increased, a series of square waves, corresponding to a 1:1 ratio with combined white and black lines, changes into a series of bell-shaped waves. This process is termed the point spread function. As a result, the contrast decreases, which makes it increasingly difficult to visualise the edge of the lines. MTF is the Fourier transformation of the point spread function. When the frequency is low and the quality ratio is one, the wave corresponds perfectly to the square waves. When the frequency increases, the ratio decreases and the wave becomes increasingly bell shaped. At an MTF of 2 %, the image will be of a uniformly grey colour (Figs. 18c & d). The CT scan limiting resolution is therefore 2 lppm at best (Fig. 18e).

_Low–contrast spatial resolution

Moreover, we can extend our discussion to the contrast level at which an image is observed and analyse low-contrast spatial resolution.[6] When the contrast decreases at high frequencies, we have to cope with a low-contrast level image that is noise dependent. Furthermore, the optical spatial resolution properties depend on the part of the screen at which we are looking. The resolution is at its best at the isocentre, worsening both in the radial direction and along the circumference, the azimuthal direction (Fig. 19). While this phenomenon holds true for the cone beam in particular, a cone-beam effect is also achieved with MSCT: the more slices we have, that is, the greater the fan beam width of each subsequent MSCT scan, the greater the cone-beam effect (Figs. 20a & b). When the isocentre is considered the central part of the radiation fan, this effect can be seen in the outermost slices of the radiation fan beam especially (Fig. 20c). Axial reconstruction algorithms report this cone-beam effect in relation to a spiral path in the axial images (Fig. 20d).[7]

Compensating cone-beam reconstruction algorithms or spiral interpolation algorithms help to solve this problem, for instance the multi-row Fourier reconstruction. Similarly, an extension of the advanced single-slice rebinning method (ASSR), which combines the idea of ASSR with a z-filtering approach, has been proposed as a solution to this problem, but its validity has not been adequately

The input frequency at which the system response approaches zero
is called the limiting frequency
the corresponding spatial resolution is called the limiting resolution
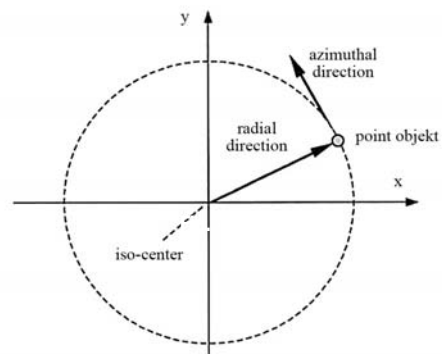
CT Limiting resolution = 0.5–2 lp/mm

Fig. 18e

Fig. 19

demonstrated. This is because, thus far, interpolation has only shown a reorientation of the optical limits for both cone beam and MSCT.[8, 9]

_Errors in sleeve placement

CT is also responsible for errors in sleeve placement inside the surgical guide. These errors are caused by an inescapable approximation in the CT resolution limits. CT cannot exceed its MTF limit, and this should be considered during planning and data transfer.

There can be repercussions on the sleeve placement inside the surgical guide, both for smooth or threaded sleeves. Sleeve position and axis are parameters associated with this procedure, and the distance to the ridge and adjacent teeth, as well as the sleeve axis, should be considered. However, from a practical perspective, they have no relevant influence on this procedure, but the limits given by these parameters are sufficient for the production of a surgical guide. Furthermore, they respect the structures adjacent to the implant site, for example plates and vascular adjacent structures, IANs, sinuses, nasal cavities, pterygopalatine fossae, mental foramina and adjacent roots.

Owing to the technical production limits of CT, the sleeve position in the surgical guide tends to be inaccurate, regardless of the technique applied (STL or stone surgery).

_Evaluation of data–transfer techniques

As for data transfer in the course of producing a surgical guide, the chosen technique should result in the sleeve being placed in the centre of the palate bone. In order to decide between CAD/CAM and stone surgery for this process, a cadaver study may help in comparing and evaluating the various techniques on the market.

In order to prove repeatability, each cadaver must be scanned several times. Each scan should consider the protocol of a different company or manufacturer. The corresponding surgical guides should be tested on the same cadaver in order to evaluate the precision of each technique in placing the sleeves in the centre of the bone, according to position and axis.

Surgical kits should fit into the mouth and I assume that the axis should respect the palate's anatomy. Furthermore, drilling and implant placement should be avoided in order to prevent inaccuracy errors other than those derived from using smooth sleeves. Likewise, a repeated scan for superimposition is not of any use. Mathematically speaking, a system can be considered reliable if its repeatability can be confirmed. In the cadaver study, the cadaver should therefore be tested to fit several repeated surgical guides. A similar technique proposed by Al-Harbi, in which the accuracy of the sleeve axis is assessed via CMM (coordinate measuring machine) and laser techniques, also appears promising.[10]

The study by Bou Serhal et al. is based on a cadaver study, but once again, the cadaver was scanned according to a superimposition protocol.[11] But why expect to obtain more information from a second CT scan if we know that CT can be imprecise? There are many articles on the reliability of CT and its correspondence to the anatomical truth, such as the studies by Lou et al.,[12] Brown et al.[13] and Damstra et al.[14]

However, these publications appear to restrict their interest to the scanned fiducial landmark measurements and record an error between 0.1 and 0.5 mm for 2-D CT. It is therefore my opinion that these studies fail to distinguish sources of error such as the MTF limit and smooth sleeves by concentrating on the superimposition of two low-quality 3-D images.

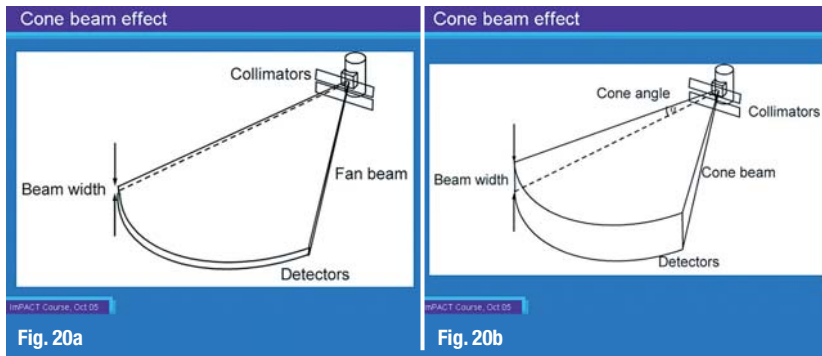Fig. 19_Radial and azimuthal resolution.

Fig. 20a

Fig. 20b

Fig. 20a–c_ Cone-beam effect.
Fig. 20d_ Cone-beam effect
interpolation.

_Reliability of STL surgical guides

The study by Stumpel[15] provides important information on the accuracy of STL surgical guides. Their reliability is ascertained via a teeth-borne surgical guide. After a stone model has been scanned and matched to the planning, the surgical guide is used like a jig and the correspondence between the STL model and the mouth is measured.

An HU threshold appropriate for the bone algorithm is necessary in order to avoid producing an STL model of inadequate size. The merging of planning and stone model scanning can further help improve its accuracy. The dimensional tolerance of an STL model is about 0.3 % when SLS or LS and stereolithography (either SL or SLA) are applied. These techniques yield tolerances of +/- 0.3 % and a minimum of +/- 0.005.

Since less resolution is needed to produce a surgical guide than to ascertain implant position, the software can only be used for planning and STL surgical guide production. It cannot, however, be used for verifying the implant position. In order to embed either smooth or thread-timed sleeves that can guide drills and implants while respecting the pt. anatomy, 0.1 mm is sufficient.

_Moving on

Superimposition cannot differentiate between inaccurate sleeve placement and inaccuracies of the

Fig. 20c

Fig. 20d

sleeve position and axis of the surgical guide or inaccuracy resulting from using a smooth sleeve. Instead, these are confused, which leads to the conclusion that a comparison of planning and post-operative scans will not lead to any convincing results, even if the superimposition was perfectly executed and different kinds of software were used in unique clinical situations. At worst, the ALARA principle cannot be followed and patients are subjected to an inordinate amount of radiation.

Once we accept that errors are likely when superimposition is done, we can consider other techniques. These techniques should be designed to avoid errors derived from using a smooth sleeve. An ideal system, for example, would allow for a prosthesis, and the surgical guide would allow for identical implant and analogue positions both in the model and in the mouth.

Thus, from now on, we can be extremely accurate when working with a thread-timed device in the implant phase. After the surgical guide has been made, we must demonstrate the accuracy of the implant placement. The surgical guide with its repeatable results allows us to work on an infinite number of master casts. Our n^{th} master cast is the mouth, and its correctness can be evaluated by means of a jig.

In 2007, Nobel engineered a threaded device for zygomatic implants, which was considered for use in other Nobel implants (patent number: WO 2007/129955 A1). Their threaded guiding sleeve functions with a threaded implant mounter. They claim that these devices lack any vertical fastening features and do not use any notches to index the hex. Consequently, they warn that there may be no hex correspondence. Therefore, additional rotation may be needed. Additional rotation amounts to missing depth (it is mathematics: if you go on screwing, you deepen the screw itself); therefore, with a threaded sleeve, missing the depth because a system has not been adequately fastened means missing the hex as well. Additional rotation is only approximately adjusting a device that has lost the phase and these two parameters. These two parameters will be missed. In order to obtain the correct final hex position (and consequently also the depth), I invented a helical gear.

_Conclusion

Accuracy in implant placement appears to depend on the context of the respective case; for example, it appears less relevant when immediate loading is not the preferred option or if an impression can be taken immediately after implant placement. However, accuracy in implant placement can
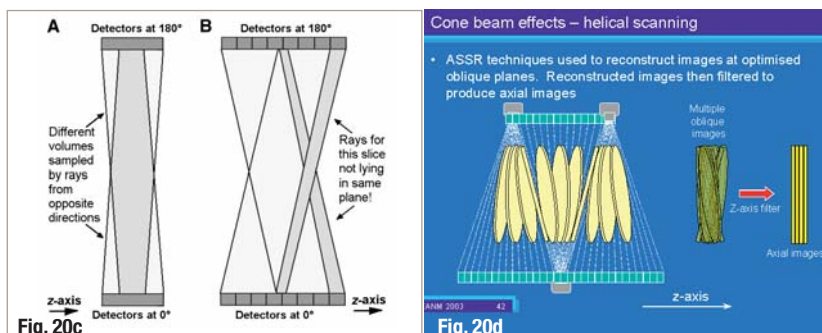
help prevent cortical vascular perfusion disorders (cortical plate perfusions) or arterial vessel damage. This appears to be especially important in areas in which hard- and soft-tissue stability is required for long-term results, for example for biomechanical concepts that require submillimetric precision. Furthermore, tissue stability should be considered in all areas of the mouth for aesthetic and trophic reasons.

On the one hand, CT scans to date offer low-resolution 3-D images of the bone. The software available, on the other hand, delivers both good planning and safe sleeve positions and axes independently of the technique used to obtain a surgical stent. However, we cannot rely on the planning, since it cannot discriminate errors. As two superimposed low-resolution 3-D images cannot result in a high quality image of the implant, relying on the planning would increase imprecision in accuracy measurements. I therefore recommend platform positioning according to mathematical criteria in order to achieve a correct, prosthetically driven position.

When sleeve placement is considered, jig correspondence between the abutments on the master cast analogues and the same abutments' clinical position on the implants can help avoid inaccuracies in terms of either the sleeve position or the axes of the surgical guide. Furthermore, it can help evaluate inaccuracies resulting from using a smooth sleeve.

To date, no publications have reported on such a technique, presumably because this kind of verification can impose too much stress on any method owing to the time required to ensure precision this way. Indeed, repeatability seems incidental to the thread-timed sleeve. Thread timing can be an impasse on the way towards a precisely placed implant, since analogues and implants cannot be forced into the same positions both repeatedly and operator independently. In other words, it is unlikely that all relevant parameters, such as the position in the ridge and the axis, the depth and the rotational feature orientation, can be taken into account.

No publications have reported on such a technique, either, simply because no method has been concerned with verifying accuracy so precisely. Repeatability is incidental to a thread-timed sleeve (that is, something able to force both analogues and implants into place in the same repeatable and operator-independent positions). Thread timing is essential. If we do not accept this, we must accept imprecision. The parameters that define the platform—position in the ridge and axis, depth and rotational feature orientation—should all be re-

spected. If we miss one parameter with a smooth sleeve we miss them all. In the case reports cited, superimposition of the planning was done after the pts. had been scanned again post-operatively. There was complete accuracy between the master model and the clinical results. In order to furthermore demonstrate how this device could work independently of the way the surgical guide is produced, no industrially manufactured surgical guides were used. Instead, a digital cast and a stone cast were used with an approximate protocol for transferring data from the software and the stone model, and plain resin was chosen as the provisional material.

Moreover, it seemed important to understand that comparing post-operative clinical CT results to the planning through superimposition can be misleading in measuring the accuracy of an implant. Contrarily, a comparison between the clinical results with either an STL or stone model on which analogues were placed by using the same threaded guiding device offers better accuracy measurement. Although software is essential to planning and creating a surgical guide with an accurately embedded sleeve, accuracy relates to the concepts of thread timing and implant phase and not to software. In the case reports cited, software was therefore used to provide qualitative data exclusively.

In general, aggressive marketing tactics are an important ethical factor when computer-guided implant placement is considered. The Millennium Research Group has estimated a 20 % growth in the number of guided implant placements by 2013. Similarly, dentists are likely to increasingly perceive the need for planning software and drilling templates. In the future, however, CAD/CAM techniques will not only be applied in planning, but also be used for surgery in order to enhance prosthesis and tissue stability. A passive device that is easy to handle and based on thread timing can pave the way to computer-guided progress._

Editorial note: A list of references is available from the publisher.

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