Virtual study models: a comparison of modular application systems

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Introduction. Virtual study models made their first appearance on the orthodontic market in 1999. The early systems offered two-dimensional images; reliable 3D images of study models were obtained only with the introduction of laser technology. Virtual study models have reduced the number of limitations and obstacles associated with the use of conventional plaster models and resulted in the creation of the "paperless orthodontic office". To understand their drawbacks, advantages and affordability, the different systems available for virtual dental casts were compared. **Discussion**. The systems envisaging the use of 3D virtual study models are: Orthocad™, e-models™, Orthoproof™, SureSmile™, Invisalign™ and Libra. All of these systems offer model "manipulation" options, whereas only Orthocad™, e-models™ and SureSmile offer advanced levels of software complexity, so as to ensure: virtual set-up, computer-aided bracket placement, planning and construction of orthodontic appliances. The use of hand-held scanners calls for highly specific skills. Basic requirements to use digital models include: a personal computer, internet access, management software. **Conclusion**. The digital elaboration of orthodontic study models is developing beyond the collection of morphologic and diagnostic data, towards the planning and production of orthodontic devices, through the use of morphing simulating the several phases of the treatment. Digital 3D models can be used at a basic and at a more advanced level, depending on the clinician's level of experience.

L. Favero, V. Favero, E. Stellini, F. Cocilovo. Virtual study models: a comparison of modular application systems. Prog Orthod 2009;10(2):20-32.

Introduction

Dental study models are an essential part of clinical practice and research for dentologists and, all the more so, for orthodontists[2]. They represent the main source of information for both the classification of malocclusions and treatment planning and a very useful tool when teaching, illustrating a case or carrying out epidemiological studies1. The guidelines for orthodontic clinical practice issued in 2003 by the American Association of Orthodontists (AAO) list them among the recommended basic records when collating adequate pre-treatment and post-treatment documentation on orthodontic patients; while Moyers[28] describes

them as one of the main sources of information for any clinical case in which a dentologist is about to engage in orthodontic treatment, as they provide a permanent 3D record of the malocclusion".

Traditionally cast out of plaster, study models perform the following key functions[31]:

- to provide information for diagnosis and the definition of treatment planning objectives…
- to provide a 3D record of the initial malocclusion, progress made during correction and orthodontic treatment outcome;
- to provide an effective communication tool, ideal when illustrating treatment outcomes to colleagues and patients, be this for didactic, assessment, research or clinical management purposes.

Recent technological advances have resulted in the generation of 3D virtual dental models which can be viewed and stored in 3D on one's personal computer.

Virtual study models do away with many of the problems and limitations encountered when using conventional plaster study models, such as[6,15,29,30]:

1. Storage and retrieval: conventional study models pose huge storage problems, as they take up space which clinical practice badly needs. Recourse to digital models instead enables storage of innumerable models in a virtual space from which they can be called up whenever needed as they are classified in user-friendly databases.
2. Transferability and communicability: given their brittleness and size, plaster study models entail considerable problems in terms of transport and transferability. Such problems can be easily overcome thanks to the introduction of virtual models. Consisting simply of a file, the digital study model can be emailed to colleagues – so as to have a second opinion on the case –, to other specialists when a multi-disciplinary treatment approach is called for or to insurance companies, for medical and legal reasons; what is more, it can be transferred to external hardware such as USB pens, CD-ROMs, DVDs or hard disks. Virtual models also represent an excellent tool when presenting clinical cases to colleagues or patients. They can also be posted, along with other clinical information on patients, on the orthodontist's web-site so as to enable patients to access their full clinical records from home. Of course, given the privacy requirements, such records will have to be protected with an adequate password system.
3. Durability: Conventional study models have a limited life-span as plaster tends to deteriorate in the course of time. Plaster is a very brittle and, when exposed to con-

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Key words: Virtual models, Laser technology, Digital elaboration, Digital management.

stant use during orthodontic treatment, it easily chips or develops fracture lines which can severely affect accuracy and reliability. The unlimited durability of virtual models makes it possible to retrieve them at a distance of years should a clinical or legal need arise and means they can be used in longitudinal epidemiological studies.

4. Diagnostic versatility: virtual study models can be used at the same time in different clinical settings and can be quickly forwarded to colleagues or other specialists. This obviously means they present innumerable advantages in diagnostic terms, especially as they can be used at the chairside in real time and easily retrieved whenever needed. Ease of retrieval and immediate visualisation of study models in the same filing system containing all other clinical data proves to be an invaluable tool, making for improved clinical diagnostic accuracy. Another advantage related to the virtual study model is the possibility of doing precise and accurated measurements, especially if compared to the ones made on plaster models.

The only drawback of virtual models – apart from the fact that, of course, they cannot be handled – is that they still couldn't be mounted and articulated: today, thanks to some new 3D Dental Scanning Systems (like 3Txer), is also possible having a window for adjustment and observation of tooth articulation. Anyway model mounting and articulation is not always called for; as Proffit points out such need arises only for adult patients presenting algic-dysfunctional symptoms or when one wishes to visualise meaningful centric occlusion - centric relation discrepancies. However, should it be of irreplaceable diagnostic value, it would be possible to obtain a "physical" copy of the model through rapid prototyping and thus easily overcome the problem.

The introduction of virtual study models will make it possible to have totally virtual clinical records for each orthodontic patient, to be used along with the by now widely popular digital x-rays and photographs, and the clinical charts contained in IT patient management programmes, all of which eventually lead to the creation of a "paperless orthodontic office"[46].

Before digital study models were devised and produced, a number of attempts had already been made to digitalise the management of orthodontic study models so as to speed up analysis, automate calculations and create a virtual archive. To do so, recourse was made to a number of techniques, as testified by photocopies[3,40], photographs[18], holographic imaging[38], "sonic digitation"[26] and scanner[29], but all these attempts were limited by the lack of three-dimensionality, inaccuracy and poor reliability. Technological progress then led

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to devices allowing for 3D model acquisition thanks to the introduction of laser scanners[16,17,27,42].

Methods based on the use of virtual study models essentially consist of two main phases[11,12]:

1. acquisition of the 3D image of the model;
2. model management by means of dedicated software.

As for the first point, scanning systems foresee the use of:

1. a laser scanner for model scanning (extraoral scanning):
   a. Destructive,
   b. Non-destructive;
2. an intra-oral scanner (direct scanning of dental arches);
3. a CT scanner for impression scanning.

The operational options offered by management software systems for three-dimensional virtual models are extremely varied and will be dealt with later on.

The main virtual models now commercially available are:

1. OrthoCAD ™;
2. E-models™;
3. Libra ortodonzia s.r.l.;
4. Orthoproof™;
5. SureSmile di Orametrix™;
6. Invisalign™.

This study sets out to analyse existing methods, both those already commercially available or those now being developed, in the field of the three-dimensional virtual imaging of dental arch study models; all this to understand both the minimum and maximum level of complexity to be found, as well as the skills required of the clinician who wants to make full use of such techniques and the methods' accessibility in terms of price. This study is based on a comparison of the different applications offered by the systems now available, of the possibility of extending them to higher levels of complexity or of the peculiar features of each.

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Discussion

The study focused on the analysis of 3D virtual imaging methods for the acquisition and clinical use of digital methods. More specifically, it was based on publications and scientific debates found in the archives of medical journals such as (for example) American Journal of Orthodontics and Dentofacial Orthopedics; European Journal of Orthodontics; Journal of clinical orthodontics; Journal of Prosthetic dentistry; Progress in Orthodontics and others like these.

Further information as to the need to create study models in the diagnostic stage, during treatment planning and when orthodontic treatment is underway was obtained by consulting such texts as R.E. Moyers' "Handbook of Orthodontics", 1991 edition, and W.R. Proffit's "Contemporary Orthodontics", second italian edition, 2000.

The most useful websites proved to be: www.orthocad.com; www.libra-ortho.it; www.orthoproof.com;

www.suresmile.com.
The key words used in the research were: Virtual Dental Casts; Digital Study Models; Three–Dimensional Imaging; Laser-Scanner; Digital Technology; Digital Orthodontics; OrthoCAD; SureSmile.

Virtual models: operational opportunities

The operational applications presented by the software for the management of virtual models include the possibility to "manipulate" the models; virtual set-up; computer-aided direct and in direct bonding; ABO post-treatment assessment; the assessment of intramaxillary basal bone relations; the creation of a "physical" model thanks to development and 3D printing techniques: stereolitography; the realisation of orthodontic devices: spoons for indirect bonding, pre-formed orthodontic arches, clear plastic orthodontic aligners for prevention or retention purposes (Invisalign™).

1. Model manipulation

Dedicated software programmes offer the following applications33:

- Simultaneous visualisation of the models from five different viewing angles: frontal, right lateral, left lateral, upper occlusal and lower occlusal.
- Visualisation and manipulation of the dynamic model with "grab and drag" option of the three-dimensional image of the model, directly using the mouse connected to the personal computer;
- Magnification of virtual models for improved point identification for diagnostic measurement purposes;
- Cross-sectioning of the models along sagittal, transversal or frontal planes so as to assess symmetry, overjet and overbite;
- Measurement of the different model components, both from point to point and from point top lane and automated calculation tools for Bolton analysis, tooth width measurements, arch width, space assessment, Tanaka- Johnston and Moyers predictions.Between 2001 and 2006, the validity, reliability, accuracy, effectiveness and reproducibility of measurements carried out on virtual models were examined by a number of authors[5,7,24,32,43,45,46] who compared the procedures that foresee the use of virtual models and those that foresee recourse to the present "gold standard", that is the manual method, in the execution of some of the diagnostic measurements.

2. Virtual set-up

Virtual set-up enables the visualisation of one or more treatment options and the comparison between these and the initial morphological situation[8,9]. The procedure to be followed for the execution of the virtual set-up is the following:

- drawing up of an orthodontic prescription form in which the orthodontist will illustrate treatment goals;
- sending of the prescription form along with the impressions and the wax bite to the supplier company;
- the first set-up is received via e-mail along with the virtual study models. At this point the orthodontist has at his disposal the initial digital models and a first occlusal set-up, and thanks to the tools offered by the management software can change the direction and grading of the tooth movements, thus obtaining a three-dimensional simulation of the same and the immediate visualization of the new location and antagonistic relations. It is possible to simulate tooth extractions, the closing or opening of spaces, the simulation of different orthodontic devices so as to identify the most suitable treatment plan for the case being examined.

3. Computer-aided bracket placement[10,33,37]

To perform this procedure one needs a pen-size wand consisting of:

- a curved tip to steer brackets on the patient's tooth surface in direct bonding, on the plaster model in indirect bonding;
- a miniature video camera projecting real time images from the area on which the bracket is being positioned;
- a white light to tack the bracket once the correct spot has been identified.

Using the wand, the practitioner transports the bracket into the patient's mouth or onto the plaster model and the whole operation is recorded by the video camera; while doing so, the practitioner is guided by the three-dimensional images of the dental arch models on which the brackets have already been virtually placed in the correct position. The

aim is to get the two images, the one projected by the camera in real time and the digital model image, to coincide. When they overlap, an audiovisual signal will inform the practitioner that the brackets have been correctly placed. The whole operation is guided by a voice providing the practitioner with correct instructions until the bracket placement operation has been completed.

4. ABO post-treatment assessment

The tools of the dedicated software include an application that makes it possible to gauge orthodontic treatment outcomes along the guidelines issued by the American Association of Orthodontics.

5. Assessment of basal bone relations

The procedure foresees the use of the information obtained from the wax bite to articulate the two models, the lower one and the upper one; it is so possible to manipulate the lower maxillary in different directions so as to assess the occlusal contact points, highlighted on the models by means of colour-coding. This makes it possible to carry out a study of the antagonistic occlusal relations between the arches.

6. Creation of a "physical equivalent" (real model)

One of the methods used for the creation of a physical equivalent of the virtual study model is a particular technique of rapid prototyping called stereolitography[4]. This method uses a liquid photo-sensitive resin which is solidified by a laser beam. The stereolitograph comprises a central container inside which the fluid resin is placed, a movable elevator platform, a laser directly connected with the computer and a deflecting mirror system which controls the laser beam. In those parts where the fluid has been crossed by the laser beam the resin solidifies and a first layer of the prototype is thus created. The procedure is continued until the whole prototype has been created. Finally, the object itself will be exposed to an ultraviolet light.

7. Creation of orthodontic devices

Once the final virtual set-up has been completed, it is emailed to the company providing the service and, basing itself on the information received, the company can produce transfer trays for indirect bonding, pre-formed orthodontic arches[21] and clear plastic aligners for prevention and retention purposes (Invisalign™)[21].

Analysis of existing methods

The need to prepare a set of study models in the diagnostic stage, in treatment planning and in treatment as such is clearly evident in orthodontics. With the introduction of computer-based virtual study models, a valid and reliable alternative to conventional ones, orthodontic study models become articulated tools which go well beyond the mere collection of diagnostic data.
All the methods were compared to assess operational options (Table 1), in particular the manipulation (Tables 3, 4) and set-up operations (Table 5) offered by the different systems as well as each system's peculiar features in terms of production costs and timing, the space taken up by the software and the models and the services offered by the manufacturers (delivery, plaster copy, impression tray return policy, storing and production of 3D models starting from the pre-existing plaster models; Table 2).

	OrthoCAD™	e-models™	Orthoproof™	SureSmile™	Libra
Manipulation	Yes	Yes	Yes	Yes	Yes
Virtual set-up	Yes	Yes	No	Yes	No
Bracket placement	Yes	Yes	No	Yes	No
Indirect bonding	Yes	Yes	No	Yes	No
Post-treatment assessment (ABO)	Yes	No	No	No	No
Jaw alignment assessment	Yes	No	No	No	No
Integration with other software systems	Yes	Yes	No	No	No
Physical equivalent (stereolitigraphy)	Yes	Yes	Yes	Yes	Yes

Tab. 1. Operational options.

	OrthoCad™	e-models™	Orthoproof™	SureSmile™	Libra
Acquisition technique	Destructive laser scanner	Non-destructive laser scanner	CT scanne	Hand-heldr intraoral scanner	Laser scanner
Cost of software	Supplied free of charge	Supplied free of charge	Supplied free of charge	Supplied upon purchase of intraoral scanner	30 €+ VAT if hired 150 €+ VAT if purchased
Cost per model	About 30 €	More expensive than OrthoCAD	N.D.	No cost once Orascanner™ has been purchased	About 30 €
Time required	5 days	5 days	3-4 days	5-10 minutes	3-5 days
Software size	8 Mb	12 Mb	Not found in product literature	Not found in product literature	2 Mb
Model size	400-800 Kb	800 Kb	Not found in product literature	Not found in product literature	2.8-5.3 Mb
Plaster copies	Additional cost	Additional cost	Additional cost	Not found in product literature	N.D.
Delivery	Internet or CD	Internet or CD	Internet or CD	Directly obtained in orthodontist's practice	Internet or CD
Creation of 3D models from pre-existing models	Yes	Yes	Yes	Yes	Yes
Storage	10 years	Unlimited	Not found in product literature	Directly obtained in orthodontist's practice	Service not offered
Impression tray return policy	Yes	Additional cost	Not found in product literature	Not used	Throwaway impression tray

Tab. 2. Aervices offered by the manufacturer.

	OrthoCAD™	e-models™	Orthoproof™	SureSmile™	Libra
Grab and drag	Yes	Yes	Yes	Yes	Yes
Rotation	Yes	Yes	Yes	Yes	Yes
Magnification	Yes	Yes	Yes	Yes	Yes
Static views	Yes	Yes	Yes	Yes	Yes
Cross-sectioning	Yes	Yes	Yes	Yes	Yes
Visualisation of occlusal contact points	Yes	Yes	No	No	No
Measurements and diagnostic calculations	Yes	Yes	Yes	Yes	Yes

Tab. 3. Manipulation.

Equipment required

The orthodontist wishing to use these systems will need some basic equipments, consisting of:

a) Personal Computer;
b) Internet connection;
c) Dedicated software.

Apart from the standard equipment, computer-aided bracket placement foresees additional hardware to be used at the chairside. It consists of a wand connected to a computer equipped with a video camera by means of which it is possible to position the brackets in the exact position previously chosen in a virtual environment.
If, instead, the procedure adopted for dental arch scanning is direct one needs an intraoral hand-held scanner.

Skills needed

When analysing the skills needed to fully exploit 3D virtual imaging approaches, one should clearly distinguish between the stage in which the 3D images of the study models are acquired and the stage in which digital models are used by having recourse to dedicated software.

Virtual model acquisition

The approaches foreseeing extraoral arch scanning by means of different devices that perform the scanning of plaster models or of dental arch impressions do not call for specific operator know-how. This because model scanning with one of the extraoral techniques now used (destructive or non-destructive laser scanner or CT scanner) is not carried out by the healthcare provider, but directly by the firm providing the service to which the orthodontist must simply send the dental arch impressions and the wax bite. It is anyway the healthcare provider's responsibility to take the impressions as accurately as possible following

	OrthoCAD™	e-models™	Orthoproof™	SureSmile™	Libra
Tooth-width measurements	Yes	Yes	Yes	Yes	
Space assessment	Yes	Yes	Yes	Yes	
Bolton analysis	Yes	Yes	Yes	Yes	
Arch width	Yes	Yes	Yes	Yes	
OJ and OB measurements	Yes	Yes	Yes	Yes	
Moyers and Tanaka-Johnson predictions	Yes	No	No	No	
Point-to-point measurements	Yes	Yes	Yes	Yes	
Point-to-plane measurements	Yes	Yes	Yes	Yes	

Tab. 4. Diagnostics.

	OrthoCad™	e-models™	SureSmile™
Tooth movements	Yes	Yes	Yes
Effect of extractions	Yes	Yes	Yes
Effect of use of different arches	Yes	Yes	Yes
Effect of different bracket positions	Yes	Yes	Yes
Treatment animation	Yes	Yes	Yes
Interproximal disking simulation	No	No	Yes
Virtual force gauce	No	No	Yes

Tab. 5. Treatment simulation/set-up.

the standard protocol and to pack them just as accurately so that the material used may preserve its features or he/she will have to send the plaster model itself. The approaches foreseeing intraoral arch scanning call instead for specific know-how, as dental arch scanning for the capture of a 3D digital image is performed directly by the clinician in the patient's oral cavity. The technique to be used to obtain an accurate analysis of every surface of the complex geometry presented by cuspids, crown grooves and tooth shapes calls for a period of training.

Dedicated software

When analysing programmes dedicated to the management and clinical use of virtual models, careful consideration should be given to the skills needed for each of the operation options available; this because the software presents different levels of complexity corresponding to different applications within the same program, requiring of the healthcare providers more and more advanced skills. As far as model "manipulation" is concerned, no special skills are required, though ability may vary from one healthcare provider to the other. The interface presented by the different systems is immediate, clear and definitely user-friendly. Anyway some time is needed to acquire familiarity with virtual reality, as the operator will have to come to terms with a different perception of depth and spatial dimensions. Clinicians used to holding plaster models in their hands need practice to get used to this new condition in which models are no longer moved or rotated manually, but by means of the mouse connected to the computer. The difficulties most frequently encountered in model manipulation have to do with the application dedicated to diagnostic measurements and calculations; more specifically with the exact identification of the meso-distal points of the dental elements. Although as one becomes more experienced, the possibility of enlarging and rotating the models allows for a more accurate identification of these points, it is initially somewhat difficult for the operator to master the technique. However, a number of studies prove that the accuracy and reliability of virtual model measurements increases as the clinician gains experience[32,43,45,46]. More specifically, Stevens et Al. Speak of a learning curve in the use of the mouse and of the different hardware systems required by this method, which is immediately mirrored in measurement and calculation accuracy. Moreover, the study carried out by Stevens et Al. on operators aged between 31 and 38 proved the learning curve was particularly steep; this means that learning times in this age bracket are particularly short as the sample population is characterised by a marked degree of IT literacy and is familiar with digital approaches in a number of activities and sectors. As for the more advanced applications of the programmes, such as virtual set-up and computer-aided bracket placement, more advanced skills are required. Optimal use of virtual set-up tools is acquired over time as it calls for mo-

re complex operations directed at the identification of different treatment plans; instead both direct bonding or computer-aided indirect bonding require a certain amount of training before clinicians become fully familiar with the specific tool dedicated to this operation. Anyway, once the operator has developed a certain skill in performing these operations, clinical operations become much faster, thanks to the greater precision offered by this system in the identification of the correct positioning of the brackets and the reduced likelihood of having to reposition the same, thus reducing clinical time at the chairside[46].

Conclusions

1. The digital processing of orthodontic study models is evolving beyond the collection of morphological and diagnostic data, towards the planning and development of orthodontic devices, through the use of morphing simulating the different treatment stages[8,21,25,37].
2. At present there are six different systems based on the use of virtual models available on the market: Cadent Ind's OrthoCAD™22, GeoDigm's e-models™, Libra ortodonzia s.r.l's 3D Models., Orthoproof™ , Orametrix™'s SureSmile™ and Invisalign produced by Align™; while others are being tested (Three dimensional digital modelling and set-up by Macchi et Al[19]).
3. The basic level of use consists of: storage in dedicated databases; 3D visualisation; manipulation; diagnostic measurements and is possible with all the above-listed systems[15,21,25 30].
4. Advanced levels of use consist of: virtual set-up, virtual bracket placement, tools for indirect bonding, computer-aided clinical bracket placement, manufacture of orthodontic devices such as spoons for indirect bonding, pre-formed orthodontic arches and clear aligners for prevention and retention purposes (Invisalign™ ecc).
5. As for the skills required, one should distinguish between the model acquisition stage and the operational and management stage:
   - The skills required for approaches involving extraoral dental arches scanning are low as this is carried out by the company supplying the models; the skills required for arch scanning by means of intraoral scanners are instead advanced.
   - The skills needed for the use of dedicated software vary depending also on the clinician's IT skills. A period of training is indeed necessary owing to the different perception of dimensions in virtual reality. The greatest problems are posed by the identification of the exact points for diagnostic calculation and by the use of the most advanced applications.
6. The equipment required for extra-oral arch scanning procedures consists of:
   - Material normally used for impression taking and wax bite;
   - Personal Computer;
   - Internet connection;
   - Dedicated software.
   - The equipment required for intraoral scanning procedures also includes a handheld intraoral scanner.

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