Working Models in the Digital Workflow: Are They Reliable?

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Purpose: This position paper summarizes all relevant aspects of the use of working models derived from digital data in digital and hybrid workflows, aiming to *(1)* provide the reader with a comprehensive review of the types of models that currently can be produced from a digital file created by an intraoral scanner (IOS); *(2)* critically analyze issues that may undermine or compromise their reliability when requested for the fabrication of both tooth-borne and implant-supported fixed dental prostheses (FDPs); and *(3)* indicate the procedures to be implemented in order to overcome these issues and produce satisfactory restorations. ***Materials and Methods:*** By way of a thorough literature review, the authors highlight the critical issues of milled and 3D-printed models, solid and alveolar, explaining the differences in terms of accuracy and reliability. ***Results and Conclusions:*** By describing the peculiarities of models with prepared natural teeth and those incorporating metal implant analogs, the clinical indications for their use are given while proposing the strategies that can be adopted to avoid errors during fabrication or to overcome inaccuracies. *Int J Prosthodont 2024;37(suppl):s227–s241. doi: 10.11607/ijp.8932*

The introduction of the intraoral scanner (IOS) in fixed prosthodontics has revolutionized the procedures for transferring clinical data to the dental laboratory. Initially, IOS data were regarded as additional information accompanying a traditional impression made with viscoelastic materials, but now it has replaced traditional methods altogether.

A *traditional dental impression* can be defined as a measurement system by contact, like a caliper or a probe. The intimate contact of the viscoelastic impression material with dental structures or implant-retained components creates, by hardening, a mold; it is possible to pour a material such as plaster or epoxy resin into this mold, creating a replica of the impressed structures.[1] Depending on the intrinsic characteristics of the impression materials, such as their hydrophilicity, detail reproduction, elasticity, tear strength, and variables related to the skills of the operator and the technique employed, an appreciably larger or smaller deviation from the intraoral situation will be found.[2,3]

The use of an IOS necessarily changes the paradigm on which traditional/conventional fixed prosthodontics is based. In this case, measurements are no longer performed

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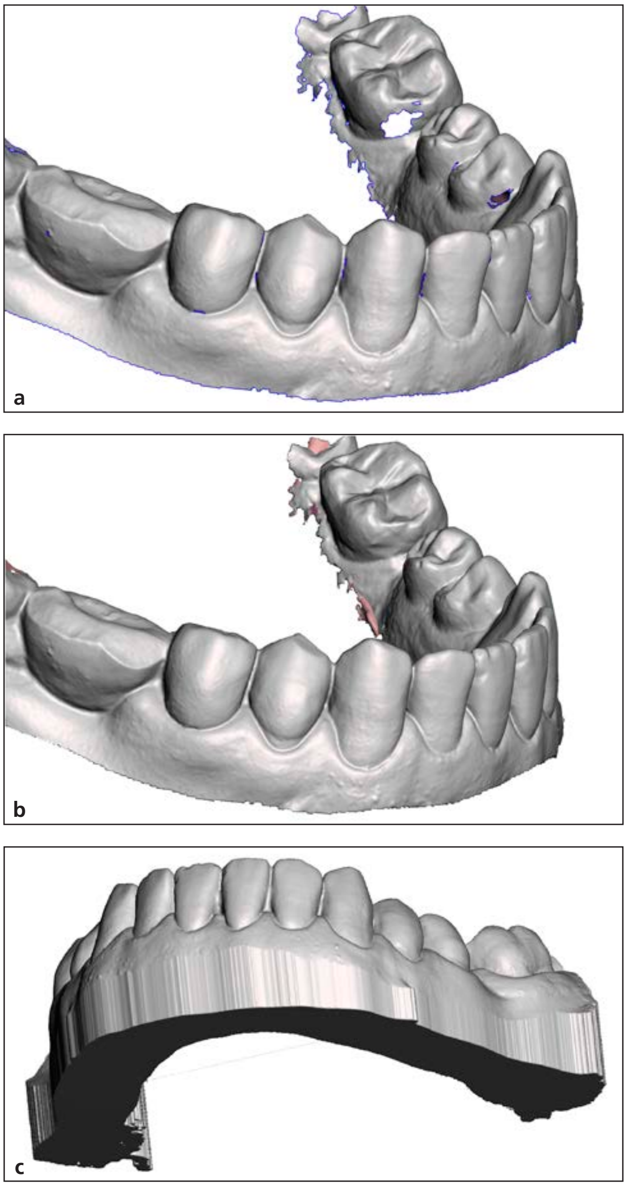


Fig 1 Transformation of the intraoral scan into a print file. *(a)* Intraoral scan with holes. *(b)* An algorithm creates a surface that corrects the lack of scan data. *(c)* The scan is transformed into a solid 3D item.

by contact but by light projection and capture of the reflection.[4,5] The IOS, through a proprietary acquired data processing algorithm, generates a representation of a virtual, not physical, model that can be viewed only through the use of a software.

At this point, the prosthetic workflow can be fully digital, traditional, or hybrid. Fully digital workflows uses computer-aided design (CAD) software, and the operator carries out the required processing (eg, creating a prosthesis) exclusively through the computer, without using a physical model. For traditional workflows, the intraoral scan is transformed into a physical model, and the fabrication phases are carried out in a traditional manner (eg, creating a physical wax-up, applying ceramic to a zirconia framework, etc). Hybrid workflows use a combination of the digital and traditional methods. For traditional and hybrid workflows, it must be evaluated whether physical models derived from digital data are similar to the models used in the analog workflow in terms of quality, accuracy, and reliability.

The scientific literature has validated the precision and accuracy of digital models used in fixed prosthodontics as being equal to those made of traditional stone poured into physical impressions.[6–12] However, factors that influence their clinical acceptability and subsequent reliability are numerous, depending on the technologies employed and whether the model is for a tooth- or an implant-supported fixed dental prosthesis (FDP).[11,13,14] Therefore, when a clinician receives an FDP fabricated on a model from digital data, the dental technician must make the clinician aware of what type of model it is considered to be—Is it a positional device to merely support the restoration without any consideration for precise spatial position and marginal accuracy, or is it a master cast onto which one can evaluate those aspects?

The present literature review demonstrates the increasing number of studies that analyze the wide range of factors affecting the reliability of physical models from digital data. However, there is yet no position paper that summarizes all relevant aspects of the evolving topic with the aim to help clinicians recognize potential pitfalls of the digital workflow when using models fabricated from digital data. Therefore, this paper aims to *(1)* provide the reader with a comprehensive review of the types of models that currently can be produced from a digital file created by an IOS; *(2)* critically analyze issues that may undermine or compromise their reliability when both tooth- and implant-supported FDPs are fabricated; and *(3)* indicate the procedures that should be followed to overcome these issues and produce satisfactory restorations.

TYPES OF MODELS

A digital scan can be transformed into a physical object using two different technologies: milling and 3D printing. First, the intraoral scan must be transformed via software into a closed solid (ie, a patch must be made of any "scan holes," which are areas that were not acquired by the IOS). This process is performed manually by a CAD operator or automatically via a dedicated algorithm (Fig 1). The scan is then ready to be transformed into a physical model by milling a volume of material (plaster, resin, metal, etc) or by building it layer-by-layer using a 3D printer and a photosensitive resin.[15]

Milled Solid Models

The milling of an object is carried out by a machine composed of a mechanical arm into which burs are

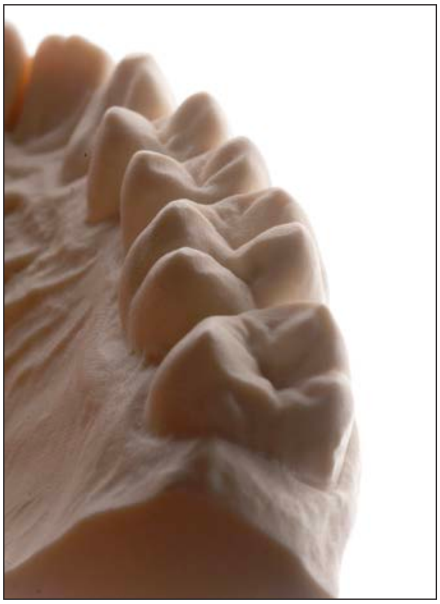


Fig 2 When a model with a high degree of detail is needed, it is possible to perform slow milling with small-diameter burs.

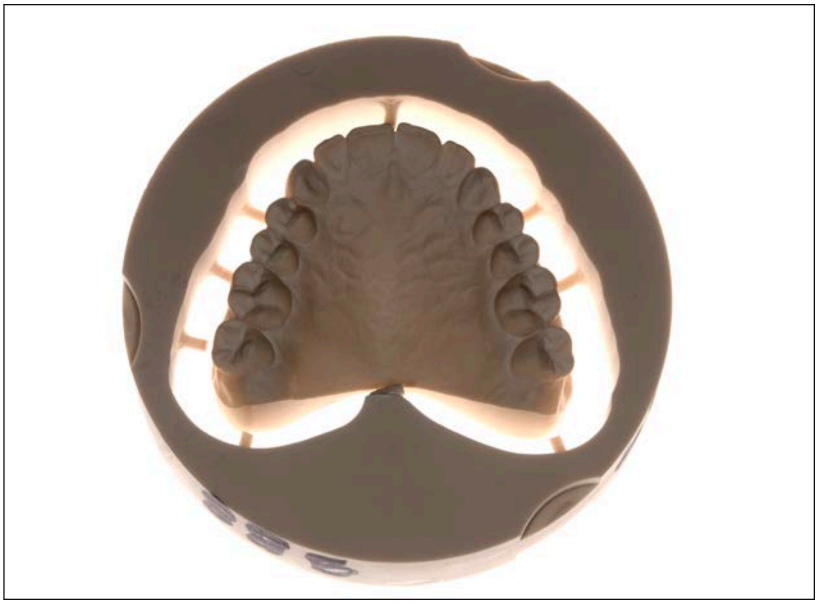


Fig 3 When the disk is embraced by a circumferential support, it is necessary to leave a portion of material so that the model can have support pins to prevent movements during milling and so that the bur can access the material without colliding with the support itself.

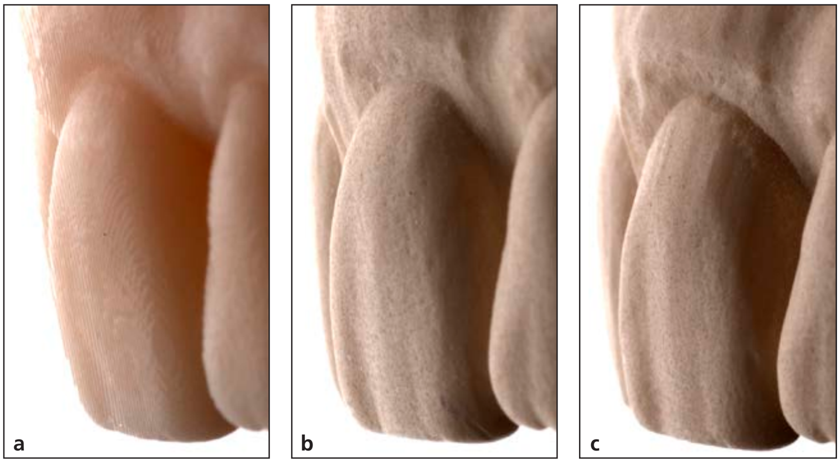


Fig 4 Anatomical shape obtained with various model production technologies. *(a)* 3D printing with DLP printer. *(b)* Milled model in which the bur has obstacle-free access. The disk has a sufficient height to be able to orient the model to expose it to 360 degrees of the milling process. *(c)* Milled model in which the bur finds an obstacle in the disc metal support and is unable to correctly replicate the shape of the cervical region of tooth 2.1. The disk is too low, and the model cannot be oriented correctly in all portions. As a consequence, the area of the tooth neck cannot be reached by the bur, and the shape is altered.

connected, a support that holds a disc of the chosen material to be excavated, and a cooling system for the bur (spray of air, water, or oil). To mill a complex object, the milling arm and the disk need to be able to perform independent articulated movements. Three-axis milling occurs when only the milling arm moves,[5] and six-axis milling occurs when the plate holding the disk is also motorized. A milling machine with a greater number of axes can perform compound movements and can therefore create complex anatomies and shapes.[7,16]

The milled model is potentially very precise, with a dimensional stability superior to that of 3D printing and with a finish and reproduction of details that can be suitable when layering ceramics or when used as an antagonist model (Fig 2).[7,17,18] As a matter of fact, the material being excavated is produced with industrial processes and is thus dimensionally stable (ie, it does not change after being milled). However, there are some technical aspects that must be known.

To make a model of a complete dental arch, the milling unit is equipped with large plates that support the disc of desired material, such as plaster or epoxy resin, in two ways: by embracing it circumferentially or by gripping it at its lower portion.[17] A circumferential support prevents the bur from accessing the material in the perimeter, and thus the disc can be milled only at a certain distance from the border and with an inclination that is never perpendicular to the edge of the disc, otherwise the bur will collide with the support (Fig 3). As shown in Fig 4, sometimes it is not possible to create the vestibular portion of the anterior teeth unless the model is inclined in a way that allows access to the bur.

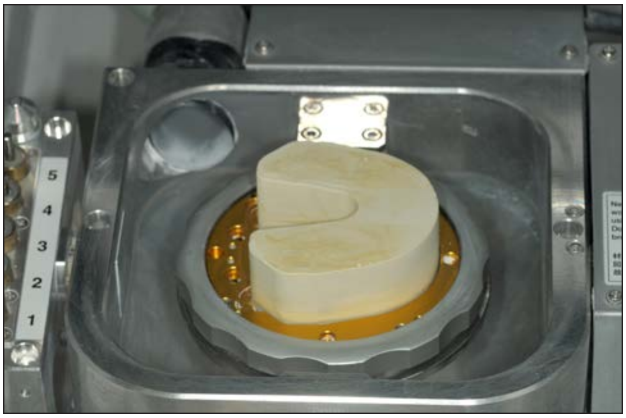


Fig 5 When the disc to be milled is held on the support by its lower portion, the bur can start removing the material even in the perimeter area, with any inclination.

Fig 6 To achieve fast and economical milling, a soft type III plaster and an intermediate finishing grade have to be used. However, this model can easily chip.

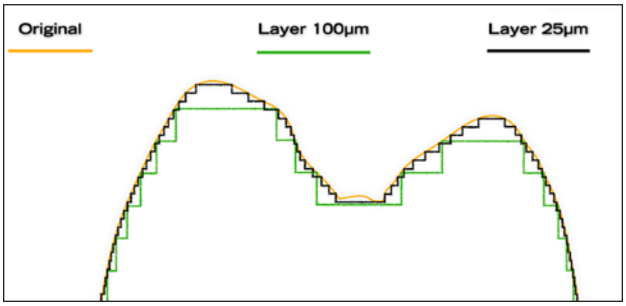


Fig 7 The choice of printing layer height determines the degree of approximation of the model in describing the object. In this cross-cut of a posterior tooth, the profile of the printed model with 100-µm layers *(green line)* and with 25-µm layers *(black line)* can be appreciated compared to the original *(yellow line)*.

Fig 8 When the print layer has a height greater than the detail to be replicated, the print does not describe the object optimally, and islands of material are created (tessellation). This model was printed with 75-µm increments.

This implies the use of thicker discs, which have higher costs and require longer milling times to remove excess material. Furthermore, pins must remain in place to keep the object firmly in position during milling, and these must be removed manually once the process is complete. When the disc is instead held at the lower portion, the perimeter material is directly accessible (Fig 5). In this case, the bur can access the disc from more angles, shortening the milling time, requiring thinner discs, and not altering the predetermined restoration anatomy.

When calculating the costs of a milled model, besides the mere cost of the material, one must consider the time spent by the milling machine. This time can vary from 2 to 4 hours, depending on the material hardness, disc thickness, and desired degree of finish.[19] Softer materials, such as type III plaster, are more easily milled and thus allow for shorter times, but these materials have limitations in quality and detail reproduction (Fig 6). With the same machine time, a dental laboratory's production yield is significantly different when milling a resin disc to create a model or a zirconium oxide disc to create crowns.[20–25] This affects the final cost of the finished product, and it is for this reason that a milled model is rarely requested.

3D-Printed Solid Models

For a solid to be printed, it must be subjected to a slicing process. Each slice is called a *layer*, and its thickness determines the ability to represent the volume in greater or lesser detail[26] (Fig 7). In other words, the layer represents the definition with which the object is described. When the software breaks down the anatomy of the model into many slices, any surface layer thinner than a layer will not be produced (Fig 8), thus creating a tessellation, which is a descriptive approximation of the object itself. The layer thickness depends upon the type of printer and the resin selected. It can range from 10 to 150 µm.[8,27]

The main variables affecting the accuracy of 3D-printed models are the type of printer,[28] composition of the resin used,[9] printing parameters,[26] model position on the printing plate,[29] model base design,[30] postpolymerization procedures,[20] and storage conditions.[21,22]

There are different types of 3D-printing technologies,[15,23,24] including fused deposition modeling (FDM),

Fig 9 When the resin for 3D-printed models does not have an adequate flexural strength and flexural modulus, the tensions and deformations can cause cracks in their surface within a matter of days.

stereolithography (SLA),[25] digital light projector (DLP),[31] continuous liquid interface production (CLIP), and polyjet photopolymer (PPP).[8,24,27,32,33] Without going into the complex technicalities of 3D-printing technology, the most common printers in dentistry are based on SLA, DLP, and LCD technologies. The substantial difference between these technologies is that SLA uses a laser that can only preliminarily polymerize the slice area point-by-point and then move on to the next layer. DLP and LCD technologies, on the other hand, project an image that covers the entire printing surface, preliminarily polymerizing the entire layer in a single step.[34] Once one layer is completed, the plate rises according to the thickness of the selected layer and prints that next layer on top of the one just created.[24,27,33] The polymerization of each layer is not completed at this stage to allow continuity/adhesion with the previous and subsequent layer and because the resin powder is dispersed in a liquid phase, which cannot be removed before the end of the printing process.[29] However, if this excess is not removed before final curing, it may create alterations to the designed shape.

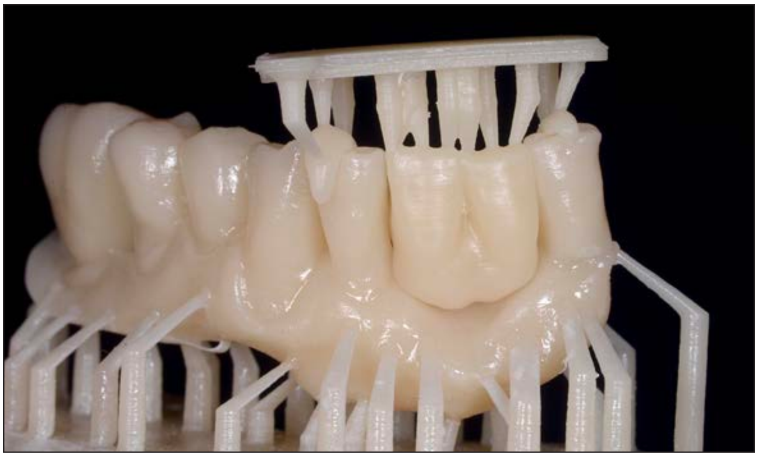
Most of the literature compared linear measurements of 3D-printed models with those of stone-cast models. Zhang[26] evaluated the accuracy of 3D-printed models using various DLP and SLA printers at different layer thicknesses and found that it was better when a 50-µm thickness was chosen. This was true for all printers. Other authors compared the accuracy and reproducibility of dental casts made by the conventional method and by 3D printing, carrying out linear[35,36] and volumetric[6,12] measurements. The outcomes demonstrated only small differences between the two types of models, and all were considered clinically acceptable. Based on these results, all of the cited authors[6,12,26,35,36] consider digital casts to be an acceptable substitute for stone casts, stating that these models are suitable for use in fixed prosthodontics.

Even if the literature supports the validity of 3D-printed models, it is undeniable that small details such as occlusal surfaces, particularly grooves and fissures, are not reproduced with the same definition as they are in a stone model. Indeed, Dong et al[37] found statistically significant differences in the average deviations of different tooth surfaces. The mean average absolute deviations of the occlusal surfaces of posterior teeth were greater than those of other surfaces.

When speaking about accuracy, do not forget that the choice of resin also plays a fundamental role. First, its particle size must be considered when deciding on the layer thickness. For example, if a clinician wants to print at a layer thickness of 50 µm with a suitable printer, it is indisputable that the diameter of the largest particle of the chosen resin must be less than this value. Second, the intrinsic properties of the resin influence the model's dimensional stability. When the resin does not meet the requirements of adequate flexural strength and flexural modulus, the model can be compromised in a very short time (Fig 9). Finally, the way the resin bottles are stored may alter the resin composition: Storing the bottle in a vertical position leads to the deposition of the heaviest particles on the bottom and of the liquid on the surface. If the bottle is not shaken for several minutes before its use (as recommended by the manufacturers in the instructions), the printed model will not have a uniform quality. Rollers are available on the market that constantly shake the bottle, maintaining a correct powder-liquid mixing ratio.

Other important aspects that influence the model accuracy are the orientation on the printing plate and the virtual placement of supports to counteract any sagging or tension that could occur during the printing

Fig 10 To limit deformation during printing, the object must be supported by pins that can only be removed after postcuring. The positioning of these supports can be carried out automatically by the model-building software that, through an algorithm, is able to analyze the critical areas and build a suitable scaffold. Alternatively, they can be designed by skilled operators.



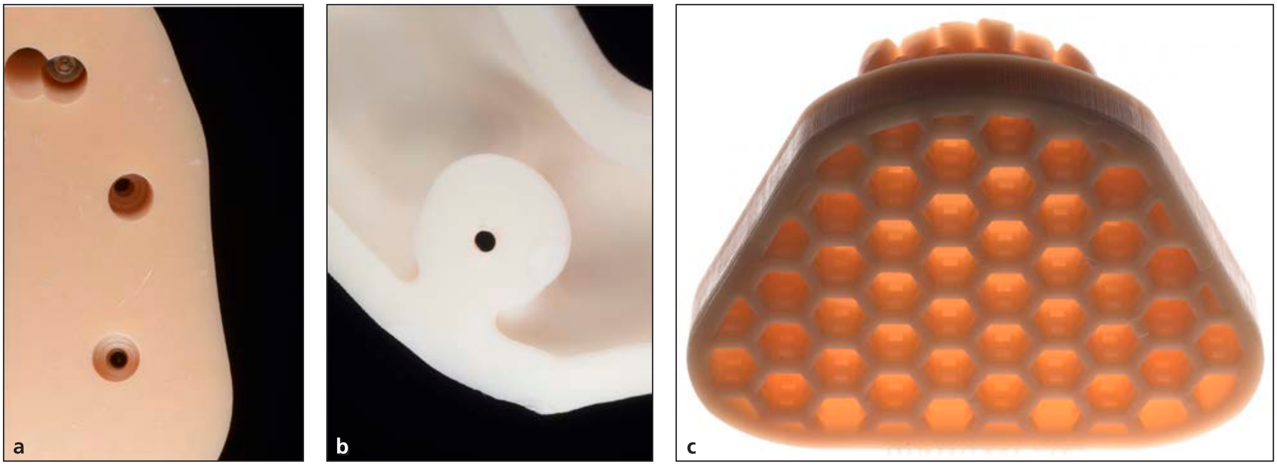


Fig 11 Various types of model bases: *(a)* solid, *(b)* hollow, and *(c)* honeycomb. The honeycomb is considered the best in absolute terms to improve accuracy.

process (Fig 10).[24,33] Regarding the orientation, it has been found that clinical acceptability was reached with any orientation (vertical and horizontal, and at 22.5, 45, and 67.5 degrees).[29] However, the best result was obtained at an angle of 22.5 degrees. Applying supports is more relevant to the accuracy of the printed model than most appreciate. This function can be carried out automatically by the model-building software, which uses an algorithm to analyze the critical areas and build a suitable scaffold. Skilled operators manually modify the position and shape of the supports when needed. To avoid undue distortions, these supports must be removed only after final curing, after tension has ceased.

Even the model base design can influence the accuracy of 3D-printed models (Fig 11). According to an investigation carried out by Revilla-León,[21] the solid and honeycomb base designs achieve the highest accuracy of the diagnostic casts fabricated with a DLP vat-polymerization printer. However, other designs (such as a hollow one) can produce models that are clinically acceptable despite the small discrepancies recorded.

The last aspect worth analyzing is the degree of resin photosensitivity. Even after final curing, the conversion rate never reaches 100%. Continued exposure to intense light sources can therefore lead to further material conversion. Because the supports and scaffolds, which kept the object in the correct shape, have already been removed at this point, a progressive modification of shape will occur over time.[21,22,38] To limit this phenomenon, it is recommended to store 3D-printed models in a dark container at a constant room temperature.[29]

Alveolar Models

As mentioned before, 3D printing and milling can achieve a high degree of finish and detail reproduction[39] but with increased production times and costs. To overcome this problem, it is possible to request an alveolar model—A model where the base is produced with one technology and the removable dies are either produced with the same technology at a different resolution or with a different technology.

Fig 12 Similar to the traditional model, it is possible to create an alveolar model with a honeycomb base and removable dies.

Fig 13 Removable dies were obtained by milling and were inserted in a printed alveolar model.

Fig 14 Removable dies were obtained by 3D printing at a high resolution and were inserted in an alveolar model printed at a lower resolution.

Fig 15 In the alveolar model base, it is possible to insert both the dies obtained by 3D printing (left central incisor) and by milling (right central incisor).

An IOS file can produce either a solid model or an alveolar model with removable dies.[26,40,41] In the latter case, the model-builder software breaks down the original file into two: the first file represents single dies of the prepared teeth, while the second one represents the model with the cavities that house the prepared teeth (Fig 12). These files can either be sent to milling machines (Fig 13) or 3D printers (Fig 14).

When a very precise die is needed (eg, to create a feldspathic ceramic veneer or to finish a milling offset of a restoration), the dies can either be milled in the material of choice or printed at the highest resolution required.[7] Then, they can be inserted into the alveolar model obtained with low-resolution SLA printing (Fig 15). This is a faster and thus less expensive procedure than making an entire model with the same settings. However, removable 3D-printed dies with different root geometries and retention mechanisms can affect the accuracy of the final model.[42] Also, a high degree of surface finish does not necessarily correspond to higher accuracy. It is necessary to check that the model does not deviate in size from the intraoral scan. This is done by superimposing the intraoral scan with the scan of the finished model (Figs 16 and 17). This is the only way to document whether the model is reliable.[7,42]

Even in the analog workflow, the creation of an alveolar model with removable dies may be characterized by a lack of accuracy and die displacement, as its construction requires multiple technique-sensitive laboratory steps and a high level of expertise.[43,44]

MODEL LIMITS FOR DENTAL- AND IMPLANT-SUPPORTED PROSTHESES

The characteristics of a model are slightly different depending on whether it is used to fabricate prostheses supported by natural or implant abutments. Natural abutments prepared to receive a prosthetic restoration have a unique preparation geometry and position in the arch. On the other hand, implants, have a standardized engagement geometry that is not printed with the model, but is incorporated in the metal laboratory analog. In this case, only the exact 3D position in the arch is needed.[45]

Fig 16 The quality of the model should not be judged by appearance. These two models were printed with the same DLP printing technology and 40-μm layers but with different resins and positioning in the printing vat. The model on the right appears truly uniform compared to the one on the left, but with a lower accuracy in replicating the intraoral scan file.

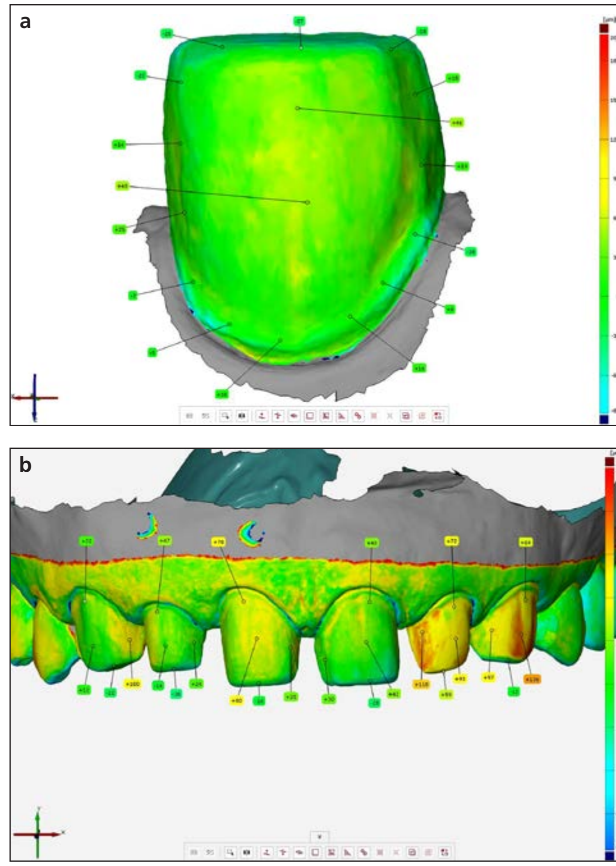


Fig 17 *(a and b)* Superimposition of the scans (from a lab scanner) of a printed die and a printed model, respectively. The relative files generated by the intraoral scan are shown. Values are expressed in microns, showing the difference between the printed model scan and the intraoral scan. In the case of the single die, the discrepancy is extremely small, but when looking at an entire model, the differences increase.

Fig 18 A 3D-printed model with the sole function of providing a stable support for the framework. For this model, veneering should only be performed on the buccal surface.

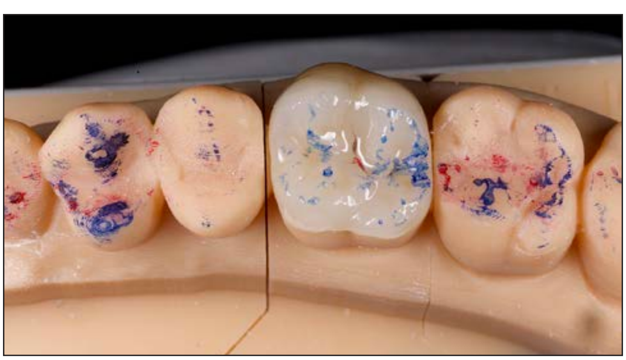


Fig 19 Models that present evident tessellation are not suitable for checking occlusal contacts or for acting as antagonistic models for veneering.

Dental Models

Depending on the requests and needs of the laboratory technician, a model can be produced to act as a positional or a precision model.

A positional model is either SLA-printed at an average or low resolution or milled with a low degree of finishing. It may be requested when the technician needs to apply a veneering ceramic only on the buccal surface of the digitally generated prostheses or if they would like to verify the morphology with respect to the neighboring and antagonist teeth (Fig 18). It is not reliable to check the presence and degree of interproximal and occlusal contacts (Fig 19).[46] These surfaces are defined very precisely in the restoration by the CAD software.

To make a comparison with the traditional workflow, this positional model is similar to the model created from a pick-up impression in which the dies are created by pouring a material (generally an autopolymerizing resin) into the incorporated prosthesis and pouring stone in the rest of the impression; the marginal precision of the prosthesis is not relevant because it has already been verified on a master model and in the mouth. When a dental prosthesis is exclusively produced via a digital workflow, its marginal precision is not to be questioned.[45,47] In this case, the only requirement of the model is to be free of dimensional distortions that can compromise the correct seating. If the margin shows gaps, it is not relevant.

Fig 20 Due to its high dimensional stability and accuracy of the abutment positions, the milled model is useful in cases with extensive rehabilitations wherein the ceramic veneering may also involve the proximal and occlusal surfaces.

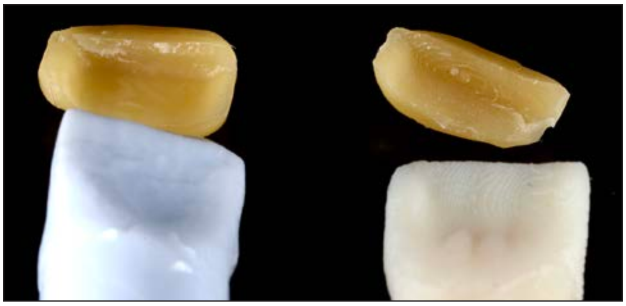


Fig 21 When wax is applied to the 3D-printed models *(right)*, a "serrated finish" is revealed compared to the milled ones *(left)*.

If not for costs and long production times, the milled model would be ideal because of its high accuracy and dimensional stability.[19,21] A precision-milled model (or die) may be requested in several instances, including whenever a physical abutment is necessary to create the restoration, such as in the case of feldspathic veneers; for this procedure, the dental technician needs an exact replica of the prepared tooth to duplicate it in a refractory material on which the ceramic is applied to obtain the correct restoration shape and marginal seal. Finally, milled models may be justified in cases wherein the ceramic veneering involves the proximal and occlusal framework surfaces (Fig 20).[48]

Even in the 3D-printed models with the highest definition, there is both layering and tessellation.[21] If wax or ceramic is applied on this die, the material fills any surface imperfections, creating the correct adaptation on the model. However, this model represents the intraoral abutment with a certain degree of approximation due to the printing layer thickness, which may cause a marginal inaccuracy. Figure 21 shows a wax coping with a "serrated finish," which generates a marginal gap once the restoration is placed in the mouth. This marginal inaccuracy is a function of the layer thickness: the thinner the layer, the more clinically acceptable the gap becomes. The best-performing printers used in dentistry today produce layers around 10 µm thick (Fig 22). This is extremely good, especially when considering that the type IV plaster used for master models in the analog workflow cannot reproduce a detail lower than 20 µm.[49]

Fig 22 If the die is made in 10-µm layers, the demarcation between layers and tessellation are difficult to appreciate; thus, it can be used to manufacture restorations with either analog or digital techniques.

Implant Models

The models with implant analogs are, to all effects, positional models; that is, they are expected to reproduce the exact position of an implant in the arch. As highlighted by Gracis et al,[50] the virtual analog position is influenced by multiple factors that can determine imprecision or noncorrespondence of the implant position.[45,47] In the case of a single implant, this inaccuracy results in errors in the interproximal and/or occlusal contact points. In the case of multiple implants that must be splinted prosthetically, position errors can easily cause a lack of passive fit of the framework.[47]

Further, there may be position discrepancies caused by a mismatch between the position of the analog in the virtual model and in the printed or milled one. Assuming that the position of the virtual analog faithfully corresponds to the intraoral position, it is necessary to analyze how 3D-printing and milling technologies create the shape of the housing for the physical implant analog. The correct position of the analog depends on two factors: creating the correct housing shape and the mechanical production tolerance of the physical analog.[45]

Fig 23 Examples of implant replicas with a nonlinear geometric shapes. If a model is created by milling, it is not possible to create a housing for them.

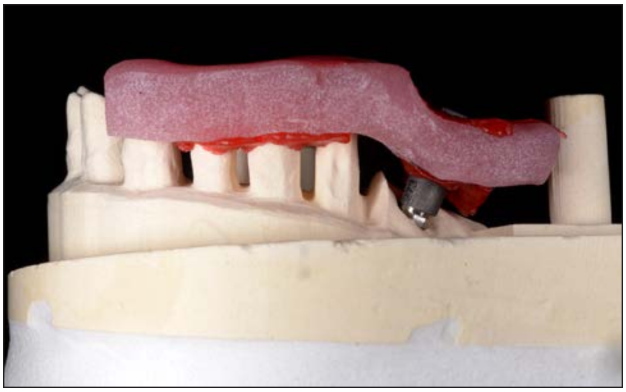


Fig 24 A physical positioner can be used to fix the analog into a milled model.

Fig 25 Cross-cut view of an implant analog housing. Due to their layered construction, 3D-printed models can replicate even complex shapes.

Fig 26 In principle, to determine a unique analog position, three areas of contact not on the same plane are sufficient *(red circles)*. When an analog is screw-retained, the vertical position is established by two opposing walls at the bottom of the housing, one represented by the screw shoulder and the other by a horizontal portion in the apical area of the analog *(blue circles)*.

Creating the correct housing shape compared to the reference library

As already emphasized, milled models are infrequently created due to production costs. In the case of implant models, there is an additional motivation: It is almost impossible to create certain shapes of implant analog housings through milling, except when the geometric shapes are linear (Fig 23). In these instances, positioners allow the technician to fix the analogs manually (Fig 24).

In the case of 3D printing, it is theoretically possible to make any geometric shape of the analog negative and therefore create the correct housing shape due to the layered construction of the model (Fig 25). But with what precision? Intimate contact between the entire analog surface and its housing is not necessary to have a unique position in the model; in theory, three areas of contact not on the same line are enough (Fig 26). However, when creating an object with 3D printing, supports that "hold" the material during printing must be provided to avoid sagging and distortions. Printing can be optimized by orienting the layers to favor correct printing, but this can only be done in the case of a single implant. In the case of multiple implants with different axes, even by a few degrees, it is not possible to orient the print layers to eliminate distortions. It is not even possible to support the holes with pins because they would then have to be removed manually, creating inaccuracies. Further, given the nature of the analog housing (small size and nonlinear shape), it is also difficult to remove any dispersed phases of printing dust. If not properly eliminated before final curing, the dust can harden, creating obstacles to the correct analog seating. Most likely, the housing presents shape distortions.[9]

Mechanical production tolerance of the physical analog

Any mechanical component is created on the basis of a geometric design with exact dimensions and measurements. On the other hand, the production of all

Fig 27 In traditional models, the tolerance of implant analogs is almost completely eliminated due to the fact that they do not have to be inserted into a housing but are instead engulfed by the material that surrounds them.

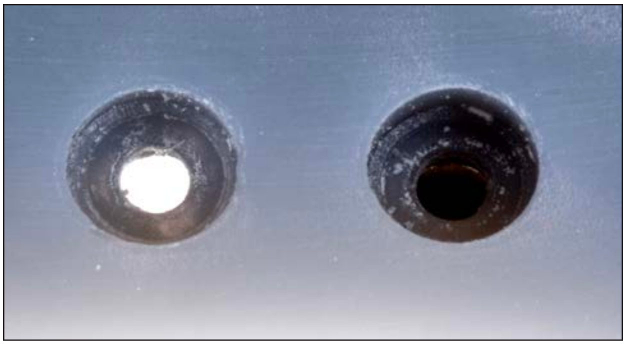


Fig 28 Screwing a metal component into a housing made of resin inevitably leads to damage of the softer material.

components does not necessarily demonstrate the same dimensional accuracy. Even if mechanical technology has made great strides, the production of parts with almost zero tolerance involves high production costs due to the use of sophisticated machines, long production times, quality materials, and high number of controls for both the machine calibration and for verifying the pieces produced. When machine parts are made, the manufacturer knows that there will be discrepancies in diameter and length. The degree of discrepancy deemed acceptable is decided arbitrarily by the company itself.

The literature has highlighted different tolerance ranges produced by various companies.[51–53] There are companies that accept ranges of ±10 μm and others that accept ranges of ±30 μm. In the case of a traditional implant impression, this dimension range does not constitute a problem, as the material that is poured to create the model incorporates the analogs, thus canceling any production tolerance (Fig 27). The analog is screwed to the impression pick-up embedded in the impression, and the position is certain. In the case of a model obtained from an intraoral scan, regardless of whether it is milled or printed, the analog must be inserted after creating the model itself. That is, printing creates the housing of the analog shape, and the component is subsequently inserted. However, this can negatively affect its position in the model. Assuming that a perfect, zero-tolerance housing can be created, inserting the analog into the housing will not be possible if the analog has the exact dimensions of the housing. The intimate contact produces friction, which prevents its positioning. If the analog diameter is larger by even just a few microns, the problem is even more visible. For the component to enter into its housing, a small negative tolerance is needed. If the negative tolerance becomes significant, there may be issues with an excessive space, and consequently the analog can have different positions. These problems may be compounded when two contiguous implants must be splinted together by a prosthesis and the two analogs have a diameter tolerance of ±30 μm each. In this case, it is possible to have a positional error of both analogs with a sum of up to 60 μm. The same concept applies to measuring the length of the analog with vertical positional errors.

Another important aspect to evaluate is the analog retention system in the housing. Having mentioned mechanical tolerances and the variables in the model printing that can influence the analog position compared to the position in the mouth, it is easy to understand why companies have introduced aids to stabilize the component in the model, such as screw- and friction-retentive aids.[9,21]

For screw retention, the lower part of the analog has a flat base with a threaded hole in the center that allows the insertion of a screw with a flat shoulder. These two flat walls work like a clamp to grip a portion of resin and lock the component in a stable position. The main advantage is that the position is stable and helps avoid any movement caused by a less-than-perfect housing or a smaller analog component (but still within the acceptable tolerance range). However, there is a very critical issue: Because the screw is made of metal and the model is made of resin, applying torque to the screw inevitably leads to an evident resin failure (Fig 28) depending on the resin and the amount of force applied. Screwing and unscrewing several times causes resin wear, which generates a positional variation (Fig 29).

The friction retention system is designed to compensate for the inevitable model printing errors. The analog is designed to have two friction areas, one each in the apical and cervical portions, while the component body is not in contact with the vertical wall of the housing (Fig 30). This reduces the probability that the analog position is influenced by shape inconsistencies caused by printing inaccuracies. Further, a friction system is less influenced by mechanical production tolerances because it needs friction, and a larger size can result in greater retention (and wear of the excess resin), while a smaller size has weaker retention but still maintains the correct position.

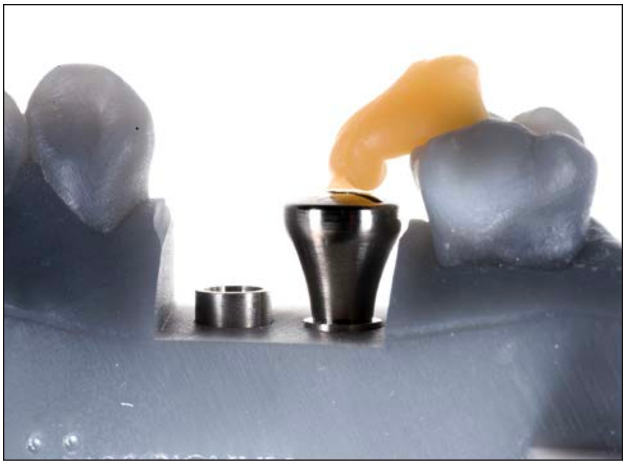


Fig 29 If the insertion and screwing procedure of a screw-retained analog is performed several times, the vertical position can be lost, as shown by the detachment of the wax from the component when the analog-retention screw is tightened.

Fig 30 An analog in its housing held by friction. It has contact in two areas: apical and coronal. The intermediate portion does not require intimate contact with the resin.

The disadvantage is that a metal component that rubs against a resinous material creates wear every time it is inserted and removed. Another disadvantage of friction systems is that, because the analog is not fixed, it can be disengaged, even partially, from its housing when a force is applied, happening during screw tightening of a nonprecise and nonpassive framework.

The horizontal portion of the analog responsible for maintaining the vertical position in the housing is a small shoulder, located in the cervical portion in friction-retained components and in the apical area in screw-retained systems (see Fig 26). The risk of having resin residues trapped in the housing—which alter the shape, once polymerized—is more frequent in areas that are difficult to clean. Therefore, having the vertical stop of the analog in the cervical area facilitates its correct positioning. In any event, it is recommended to add grooves that interrupt the horizontal stop portion to allow any resin residues to flow into small reservoirs.

It follows that the analog position on the models obtained from the intraoral scan, both screw- and friction-retained, cannot be considered precise and reliable for verifying the passivity of the prosthetic structures. Even if the printers, materials, and printing processes constantly improve, the problem will continue to exist until companies reduce the analog's tolerance parameters.

To determine whether the analog position on the model is correct, connect the scan abutments used for the intraoral scan (oriented in the same way), make a scan with a laboratory scanner, and superimpose the two files. This will numerically demonstrate the degree of reliability. A virtual model, on the other hand, does not include mechanical production errors, as it incorporates the exact dimensions of digital libraries. An entirely digital workflow therefore has a potentially higher degree of precision.

HOW TO OVERCOME THE LIMITATIONS OF IMPLANT MODELS IN THE DIGITAL WORKFLOW

Having explained the reasons why it cannot be assumed that implant models generated from a digital impression are precise, it is important to analyze the protocols and solutions to adopt when creating prosthetic restorations with multiple splinted implants.

When a screw-retained prostheses is created by CAD/CAM milling and includes the connections to the implants, as seen for prostheses on multiunit abutments or with a flat-to-flat connection, a model is needed only as a support for veneering the framework with an esthetic material[54] (Fig 31). In these cases, the lack of absolute precision in the relative position of the analogs does not negatively impact the outcome (except for the interproximal contact points[54]) because the framework is created virtually, where the analogs have no mechanical tolerance. Small discrepancies are compensated for due to the inevitable tolerance in the implant connection itself.

However, if the restoration has to be fixed to the implants using an intermediate component, whether a prefabricated (titanium base) or individualized abutment, the model must accurately reproduce the implant positions so that the prosthesis can be glued without incorporating inaccuracies. Freehand fixation would lead to major discrepancies. To achieve a successful outcome, there are three possible scenarios.

In the first scenario, prior to manufacturing the definitive prostheses, a jig is created and tried in the mouth. It can either be in aluminum or polymethyl methacrylate (PMMA) milled from the CAD file (Fig 32). If the jig is precise, it proves that the model is reliable, and it can serve as a template for creating a gluing base. If it is incorrect and there is either tension during screwing

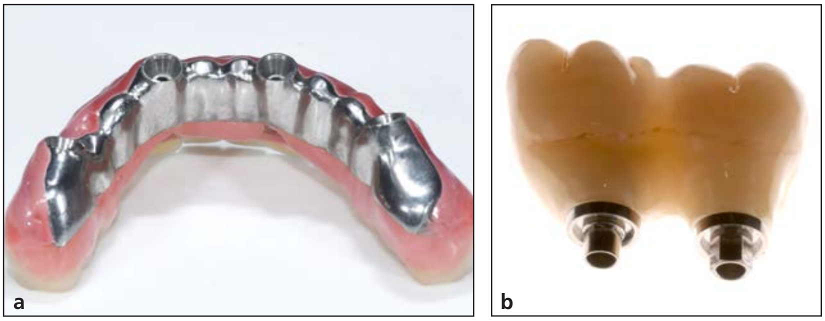


Fig 31 *(a)* An implant-supported FPD with a built-in connection in the framework. *(b)* A zirconia framework glued to intermediate abutments.

Fig 32 A milled aluminum jig can be created to verify the correspondence between the implant positions in the intraoral scan and the real position in the patient's mouth.

Fig 33 Implant scan abutments can be joined and splinted with resin in the patient's mouth during the same appointment as the intraoral scan. The material that holds and connects the implant components must have high dimensional stability.

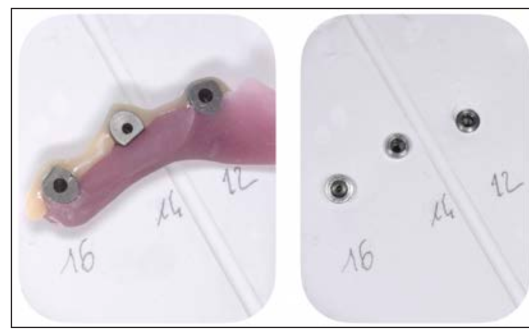


Fig 34 A plaster model made from the intraoral jig captured the implant positions. Because there are no reference structures (due to the lack of the neighboring teeth), it is useful to indicate to the technician the numbering of the various implants to identify their position without any doubt.

or insertion difficulties, it is separated with a disc, and the segment positions are captured with an index in plaster or autopolymerizing resin. Then, a new model is created and will be used for gluing at the end of the manufacturing process. Compared to an aluminum jig, a PMMA jig or prototype does not provide the same degree of certainty. In fact, the material is not as rigid as metal and, by becoming deformed when the screws are tightened, could easily hide small positional discrepancies. Using radiographs to check for passive fit is not a fail-safe strategy.[55,56]

In the second scenario, the model is printed from the IOS file, and a plaster verification key is then fabricated, incorporating screw-retained temporary cylinders on the implant analogs in the model. The device is tried in the mouth. If there is a discrepancy with the intraoral situation, the plaster verification key will fracture when tightening the screws of the temporary cylinders. In such a case, notches can be created, and the correct position can be recorded with the same plaster.

In the third scenario, after making the intraoral scan, a physical sectional impression is also taken to avoid an additional appointment for verifying the implant positions with a jig. Impression copings are connected to the implants in the patient's mouth; joined together with resin, plaster, or metal rods; and fixed with a light-curing composite (Fig 33). As soon as it is removed from the mouth, a model is created by screwing analogs to the components embedded in the material and then pouring plaster (Fig 34).

In the present authors' experience, all of these methods have proven to be very effective in creating an efficient workflow.

CONCLUSIONS

A digital workflow, with the possible exception of a single monolithic crown on either teeth or implants, cannot be carried out without the use of a model.[57–59] However, the models produced from digital files cannot be assumed to be completely accurate and reliable.

From what has been described in this paper, the present authors have reached the following conclusions:

1. The decision of whether the model generated from an intraoral scan is suitable only for providing support to the digitally generated prostheses or is precise enough to manufacture or refine restorations depends on the type of request received from the clinician; the former

is for manufacturing monolithic restorations or restorations veneered only on the buccal surface, while the latter is indicated when also veneering the proximal and occlusal surfaces.

2. The maximum accuracy in the relative position between abutments in tooth-supported FDPs is obtained with a milled model, but 3D-printed solid models are considered clinically acceptable when layered in 50-μm increments;
3. 3D-printed alveolar models provide at least two advantages: *(1)* printing highly defined removable dies reduces costs compared to producing an entire model with the same degree of definition while providing a reliable copy of the natural abutment; and *(2)* removable dies allow a 360-degree view of the restoration adaptation and are thus convenient when offset elimination is needed;
4. Implant models for frameworks with built-in connections on flat implant shoulders or multiunit abutments are merely positional models, and the analog tolerance does not play any role in their fit;
5. When manufacturing implant-supported FDPs that have to be glued to prefabricated components (eg, Ti-bases), the model plays an important role and thus needs to be verified through the superimposition of the scan of the model and the intraoral scan. In fact, because of the high tolerances in the implant analogs, clinicians cannot be sure that their position in the 3D-printed implant model is accurate;
6. Whenever the two scans are not superimposed or if the implant model is found to be imprecise, it is recommended to fabricate a verification jig to validate the implant positions prior to manufacturing the FDP; if found to be different, the jig allows the actual positions to be captured.

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REFERENCES

1. Punj A, Bompolaki D, Garaicoa J. Dental impression materials and techniques. Dent Clin North Am 2017;61:779–796.
2. Giménez B, Özcan M, Martínez-Rus F, Pradíes G. Accuracy of a digital impression system based on active triangulation technology with blue light for implants: Effect of clinically relevant parameters. Implant Dent 2015;24:498–504.
3. Giménez B, Pradíes G, Martínez-Rus F, Özcan M. Accuracy of two digital implant impression systems based on confocal microscopy with variations in customized software and clinical parameters. Int J Oral Maxillofac Implants 2015;30:56–64.
4. Richert R, Goujat A, Venet L, et al. Intraoral scanner technologies: A review to make a successful impression. J Healthc Eng 2017;2017:8427595.
5. van der Meer WJ, Andriessen FS, Wismeijer D, Ren Y. Application of intra-oral dental scanners in the digital workflow of implantology. PLoS One 2012;7:e43312.
6. Aly P, Mohsen C. Comparison of the accuracy of three-dimensional printed casts, digital, and conventional casts: An in vitro study. Our J Dent 2020;14:189–193.
7. Choi JW, Ahn JJ, Son K, Huh JB. Three-dimensional evaluation on accuracy of conventional and milled gypsum models and 3d printed photopolymer models. Materials 2019;12:3499.
8. You SM, You SG, Kang SY, Bae SY, Kim JH. Evaluation of the accuracy (trueness and precision) of a maxillary trial denture according to the layer thickness: An in vitro study. J Prosthet Dent 2021;125:139–145.
9. Revilla-León M, Fogarty R, Barrington JJ, Zandinejad A, Özcan M. Influence of scan body design and digital implant analogs on implant replica position in additively manufactured casts. J Prosthet Dent 2020;124:202–210.
10. Parize H, Dias Corpa Tardelli J, Bohner L, Sesma N, Muglia VA, Cândido Dos Reis A. Digital versus conventional workflow for the fabrication of physical casts for fixed prosthodontics: A systematic review of accuracy. J Prosthet Dent 2022;128:25–32.
11. Papaspyridakos P, Chen YW, Alshawaf B, et al. Digital workflow: In vitro accuracy of 3D printed casts generated from complete-arch digital implant scans. J Prosthet Dent 2020;124:589–593.
12. Banjar A, Chen YW, Kostagianni A, et al. Accuracy of 3D printed implant casts versus stone casts: A comparative study in the anterior maxilla. J Prosthodont 2021;30:783–788.
13. Buda M, Bratos M, Sorensen JA. Accuracy of 3-dimensional computer-aided manufactured single-tooth implant definitive casts. J Prosthet Dent 2018;120:913–918.
14. Gagnon-Audet A, An H, Jensen UF, Bratos M, Sorensen JA. Trueness of 3-dimensionally printed complete arch implant analog casts. J Prosthet Dent 2023;S0022-3913(23)00421-3.
15. Alammar A, Kois JC, Revilla-León M, Att W. Additive manufacturing technologies: Current status and future perspectives. J Prosthodont 2022;31:4–12.
16. Anadioti E, Kane B, Zhang Y, Bergler M, Mante F, Blatz MB. Accuracy of dental and industrial 3D printers. J Prosthodont 2022;31:30–37.
17. Alghazzawi TF. Advancements in CAD/CAM technology: Options for practical implementation. J Prosthodont Res 2016;60:72–84.
18. Figueras-Alvarez O, Cantó-Navés O, Real-Voltas F, Roig M. Protocol for the clinical assessment of passive fit for multiple implant-supported prostheses: A dental technique. J Prosthet Dent 2021;126:727–730.
19. Koch GK, Gallucci GO, Lee SJ. Accuracy in the digital workflow: From data acquisition to the digitally milled cast. J Prosthet Dent 2016;115:749–754.
20. Kim JH, Kwon JS, Park JM, Lo Russo L, Shim JS. Effects of postpolymerization conditions on the physical properties, cytotoxicity, and dimensional accuracy of a 3D-printed dental restorative material. J Prosthet Dent 2022:S0022-3913(22)00281-5.
21. Revilla-León M, Piedra-Cascón W, Aragoneses R, et al. Influence of base design on the manufacturing accuracy of vat-polymerized diagnostic casts: An in vitro study. J Prosthet Dent 2023;129:166–173.
22. Yousef H, Harris BT, Elathamna EN, Morton D, Lin WS. Effect of additive manufacturing process and storage condition on the dimensional accuracy and stability of 3D-printed dental casts. J Prosthet Dent 2022;128:1041–1046.
23. Park JM, Jeon J, Koak JY, Kim SK, Heo SJ. Dimensional accuracy and surface characteristics of 3D-printed dental casts. J Prosthet Dent 2021;126:427–437.
24. Quan H, Zhang T, Xu H, Luo S, Nie J, Zhu X. Photo-curing 3D printing technique and its challenges. Bioact Mater 2020;5:110–115
25. Hull CW [inventor]. 3D Systems Inc, assignee. Apparatus for production of three-dimensional objects by stereolithography. US patent US4575330A. 1986.
26. Zhang ZC, Li PL, Chu FT, Shen G. Influence of the three-dimensional printing technique and printing layer thickness on model accuracy. J Orofac Orthop 2019;80:194–204.
27. Revilla-León M, Özcan M. Additive manufacturing technologies used for processing polymers: Current status and potential application in prosthetic dentistry. J Prosthodont 2019;28:146–158.

28. Morón-Conejo B, López-Vilagran J, Cáceres D, Berrendero S, Pradíes G. Accuracy of five different 3D printing workflows for dental models comparing industrial and dental desktop printers. Clin Oral Investig 2023;27:2521–2532.
29. Maneiro Lojo J, Alonso Pérez-Barquero J, García-Sala Bonmatí F, Agustín-Panadero R, Yilmaz B, Revilla-León M. Influence of print orientation on the accuracy (trueness and precision) of diagnostic casts manufactured with a daylight polymer printer. J Prosthet Dent 2023;S0022-3913(23)00076-8.
30. Alharbi N, Osman R, Wismeijer D. Effects of build direction on the mechanical properties of 3D-printed complete coverage interim dental restorations. J Prosthet Dent 2016;115:760–767.
31. Hornbeck LJ [inventor]. Texas Instruments Inc, assignee. Multi-level digital micromirror device. US patent 5.061.049. 1990.
32. Schweiger J, Edelhoff D, Güth JF. 3D printing in digital prosthetic dentistry: An overview of recent developments in additive manufacturing. J Clin Med 2021;10:2010.
33. Dawood A, Marti Marti B, Sauret-Jackson V, Darwood A. 3D printing in dentistry. Br Dent J 2015;219:521–529.
34. Vlasa A, Bocanet VI, Muntean MH, et al. Accuracy of three-dimensional printed dental models based on ethylene di-methacrylate-stereolithography (SLA) vs. digital light processing (DLP). Appl Sci 2023;13:2664–2673.
35. Park ME, Shin SY. Three-dimensional comparative study on the accuracy and reproducibility of dental casts fabricated by 3D printers. J Prosthet Dent 2018;119:861.e1–e7.
36. Brown GB, Currier GF, Kadioglu O, Kierl JP. Accuracy of 3-dimensional printed dental models reconstructed from digital intraoral impressions. Am J Orthod Dentofacial Orthop 2018;154:733–739.
37. Dong T, Wang X, Xia L, Yuan L, Ye N, Fang B. Accuracy of different tooth surfaces on 3D printed dental models: Orthodontic perspective. BMC Oral Health 2020;20:340–348.
38. Schweiger J, Güth JF, Edelhoff D, Seidel K, Graf T. Application of 3D-printed colored 3D-models for the fabrication of full ceramic restorations: A technical report. J Esthet Restor Dent 2022;34:235–243.
39. Yilmaz B, Donmez MB, Kahveci Ç, et al. Effect of printing layer thickness on the trueness and fit of additively manufactured removable dies. J Prosthet Dent 2022;128:1318.e1–e9.
40. Van Noort R. The future of dental devices is digital. Dent Mater 2012;28:3–12.
41. Emir F, Ayyildiz S. Accuracy evaluation of complete-arch models manufactured by three different 3D printing technologies: A three-dimensional analysis. J Prosthodont Res 2021;65:365–370.
42. Azpiazu-Flores FX, Johnston WM, Mata-Mata SJ, Yilmaz B. Positional trueness of three removable die designs with different root geometries manufactured using stereolithographic 3D printing. J Prosthet Dent 2023:S0022–3913(23)00606-6.
43. Magne M, Panaghiotis P, Magne P. The alveolar model. Quintessence Dent Technol 2008;32:39–46.
44. Anusavice KJ, Phillips RW, Skinner EW. Part IV: Chapter 13. In: Phillips' Science of Dental Materials, ed 13. Elsevier, 2022:275–302.
45. Olea-Vielba M, Jareño-García D, Methani MM, Martinez-Klemm I, Revilla-León M. Accuracy of the implant replica positions on the complete edentulous additive manufactured cast. J Prosthodont 2020;29:780–786.
46. Young Kim RJ, Cho SM, Jung WS, Park JM. Trueness and surface characteristics of 3-dimensional printed casts made with different technologies. J Prosthet Dent 2023; S0022–3913(22)00750-8.
47. Michelinakis G, Apostolakis D, Kamposiora P, Papavasiliou G, Özcan M. The direct digital workflow in fixed implant prosthodontics: A narrative review. BMC Oral Health 2021;21:37.
48. Jha R, Jain V, Das TK, Shah N, Pruthi G. Comparison of marginal fidelity and surface roughness of porcelain veneers fabricated by refractory die and pressing techniques. J Prosthodont 2013;22:439–444.
49. Gujjarlapudi MC, Reddy SV, Madineni PK, Ealla KK, Nunna VN, Manne SD. Comparative evaluation of few physical properties of epoxy resin, resin-modified gypsum and conventional type IV gypsum die materials: An in vitro study. J Contemp Dent Pract 2012;13:48–54.
50. Gracis S, Appiani A, Noè G. Digital workflow in implant prosthodontics: The critical aspects for reliable accuracy. J Esthet Restor Dent 2023;35:250–261.
51. Ma T, Nicholls JI, Rubenstein JE. Tolerance measurements of various implant components. Int J Oral Maxillofac Implants 1997;12:371–375.
52. Braian M, De Bruyn H, Fransson H, Christersson C, Wennerberg A. Tolerance measurements on internal- and external-hexagon implants. Int J Oral Maxillofac Implants 2014;29:846–852.
53. Paratelli A, Vania S, Gómez-Polo C, Ortega R, Revilla-León M, Gómez-Polo M. Techniques to improve the accuracy of complete arch implant intraoral digital scans: A systematic review. J Prosthet Dent 2023;129:844–854.
54. Yilmaz B, Alshahrani FA, Kale E, Johnston WM. Effect of feldspathic porcelain layering on the marginal fit of zirconia and titanium complete-arch fixed implant-supported frameworks. J Prosthet Dent 2018;120:71–78.
55. Darós P, Carneiro VC, Siqueira AP, de-Azevedo-Vaz SL. Diagnostic accuracy of 4 intraoral radiographic techniques for misfit detection at the implant abutment joint. J Prosthet Dent 2018;120:57–64.
56. Turkyilmaz I, Wilkins GN. 3D printing in dentistry—Exploring the new horizons. J Dent Sci 2021;16:1037–1038.
57. Boeddinghaus M, Breloer ES, Rehmann P, Wöstmann B. Accuracy of single-tooth restorations based on intraoral digital and conventional impressions in patients. Clin Oral Investig 2015;19:2027–2034.
58. Gianfreda F, Pesce P, Marcano E, Pistilli V, Bollero P, Canullo L. Clinical outcome of fully digital workflow for single-implant-supported crowns: A retrospective clinical study. Dent J (Basel) 2022;10:139.
59. Valenti M, Valenti A, Schmitz JH, Cortellini D, Canale A. Survival analysis up to 7 years of 621 zirconia monolithic single crowns with feather-edge margins fabricated with a cast-free workflow starting from intraoral scans: A multicentric retrospective study. J Prosthet Dent 2023;129:76–82.