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Historical development of root analogue implants: a review of published papers

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Abstract

The timetable for placing a dental implant can be crucial in the reduction of resorption of the socket after an extraction. The association of immediate implantation with an implant that copies the anatomy of the extracted root seems to add benefits in limiting the hard and soft tissue changes that may occur. The purpose of this paper is to provide an overview of the historical development of all types of root analogue implants from their beginning to the present day. To our knowledge the first individualised ones were described in 1969. Later, the use of titanium instead of the polymers that were used to start with offered better bony integration, and showed that the selection of materials was a key factor in their success. Root analogue implants made from zirconia were also described when attempts were being made to improve aesthetics in the anterior regions. The more recent introduction of digital technology such as DICOM has allowed the fabrication of these implants in less time, and the combination with digital diagnostic options such as cone-beam computed tomography facilitated the fabrication of some types of implants before extraction that could be inserted immediately into the alveolar socket with optimal and safe 3-dimensional positioning. Currently digital planning allows the clinician to design the ideal implant and abutment, which reduces the need for tissue grafting in the surgical phase and gingival conditioning in the prosthetic phase.

Keywords: root analogue implants; CAD/CAM technology; cone beam tomography; zirconia; titanium

Introduction

Dental implants are an optimal way of replacing missing teeth, as they have good long-term success rates of up to 90% or more.[1] After a tooth has been extracted there is an inevitable remodelling of the socket, which can limit the placing of an implant. The continuous resorption can reach up to 63% on horizontal and 11%-22% on vertical alveolar bone within six months.[2] Alterations of the dimensions of the alveolar socket on the buccal wall are related to the resorption of the bundle bone, a tooth-dependent structure that is left after the extraction with few or no vessels for its blood supply.[2–5]

It has been reported that the immediate use of implants might control these alterations to the ridge by reducing the speed of resorption of the socket.[6] The main advantage of immediate implants is that the overall duration of treatment, cost, and number of surgical interventions can be reduced,[6]

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but the operator usually has to face some surgical challenges in this approach, including: difficulty in achieving primary stability and controlling the 3-dimensional position of the implant; discrepancies between the sizes of the implant and the socket; the poor quality of bone that is often present in the extraction socket; and the need to prepare the socket with drilling burrs that can overheat the bone. [7–11] These challenges are related to the characteristics of conventional implants, mainly the standardised sizes and shapes.

To overcome these challenges, the use of an immediate implant with the same design as the extracted root is thought to be highly beneficial.[8] This patient-individual concept, known as root analogue implant, was first described in 1969,[12] and was fabricated from an autopolymerised and heat-processed poly methylmethacrylate material. However, this approach was considered unsuccessful because the implant became fibrointegrated (or encapsulated) instead of osseointegrated, and this resulted in the abandonment of this type of root analogue implant.[8–13]

The technique was reintroduced in 1992 using different materials to fabricate the implant, as well as various methods of fabrication.[13] The use of titanium instead of polymers gave an osseointegration rate of 88%, which highlighted the fact that selection of the material is as important a factor for the success of the implant as an optimal fit between the implant and the socket.

Titanium is nowadays considered to be the material of choice for dental implants, but several zirconia-based implant systems are available and a root analogue implant can be fabricated from zirconia.[8] The choice of zirconia improves the aesthetic result, particularly in the anterior region, which avoids the aesthetic impairment often caused by the greyish discolouration in the soft tissue that is caused by titanium implants and abutments.[8,14] Recently, a technique that used a titanium root and a zirconia abutment was introduced into the dental market. Besides the possible improvements in aesthetics of this design, the zirconia abutment is fused to the titanium root by a sintering process, which eliminates any microgap (which has been reported to be a possible cause of appreciable bone loss around the implant during remodeling).[15]

As well as the beneficial shape of root analogue implants, the development of techniques such as cone-beam computed tomography (CT) and computer-aided design/computer-aided manufacturing (CAD/CAM) offers the fabrication of such implants before, and placement immediately after, extraction. This facilitates the whole procedure by allowing safe 3-dimensional positioning of the implant with optimal design of the abutment, and the might reduce the need for hard and soft tissue grafts and the number of appointments for gingival conditioning (that may affect the soft tissue surrounding the implant).[8,16,17]

Considering that immediate implantation can show some important benefits, some difficulties might be encountered with the insertion of conventional implants. The use of root analogue implants associated with the described preoperative fabrication might turn the surgical and prosthetic phase into a simpler and a more predictable treatment in selected cases. Because of the number of types of implant and fabrication methods that have been published, the aim of this article was to provide a detailed overview of their historical development from the first ideas to the current state of affairs, combined with a special focus on the comparison between the ReImplant® System and the modern Replicate™ System.

Historical overview of root analogue implants

A historical overview of root analogue implants including name, version, material, fabrication process, surface, number of parts, clinical applications, insertion technique, and possibility of immediate loading is shown in Fig. 1.

The dental polymer implant concept

The dental polymer implant was the first root polymer implant, and its description was published in 1969.[12] Materials for the polymer were selected because: they could possibly be "tailored" to specific needs through the addition or removal of ingredients to change their physical characteristics; for their ease of handling and accuracy of reproduction; microwave or electric current emissions, as with metals, were absent; they had a better fibrous connective tissue attachment; and there was the possibility of microscopic evaluation.[12] An autopolymerising and heat-processed polymethacrylate, alone or combined with grated cancellous freeze-dried calf bone, was used to fabricate the implant, and the process was done after extraction. The tooth was cleaned, and any surface defect was corrected with wax, then a mould was made by investing the tooth in stone or plaster, applying a hydrocolloid separating medium to the plaster, and packing the polymer into the flask. The heat polymerisation process was at a temperature and time recommended for the specific material. The surface was pretreated by airborne particle abrasion with corundum and sterilised with a 10-minute immersion in zephiran chloride®. The size and shape of the implant were compared with those of the tooth, and the replica could be installed 45 minutes after extraction. The authors recommended splinting the implant to the adjacent teeth or implants during healing.[12] Over the years, new studies have reported that the polymethacrylate root analogue implant became mainly encapsulated by soft tissue (fibrointegration) instead of osseointegrated, leading to the discontinuation of this technique.[1,7,8,18]

The root analogue titanium implants

Root analogue implants were reintroduced in 1992, this time made of pure titanium, and the first research was done in dogs.[13] The teeth were extracted, and each extracted root was machine-copied to a titanium analogue. The machine-

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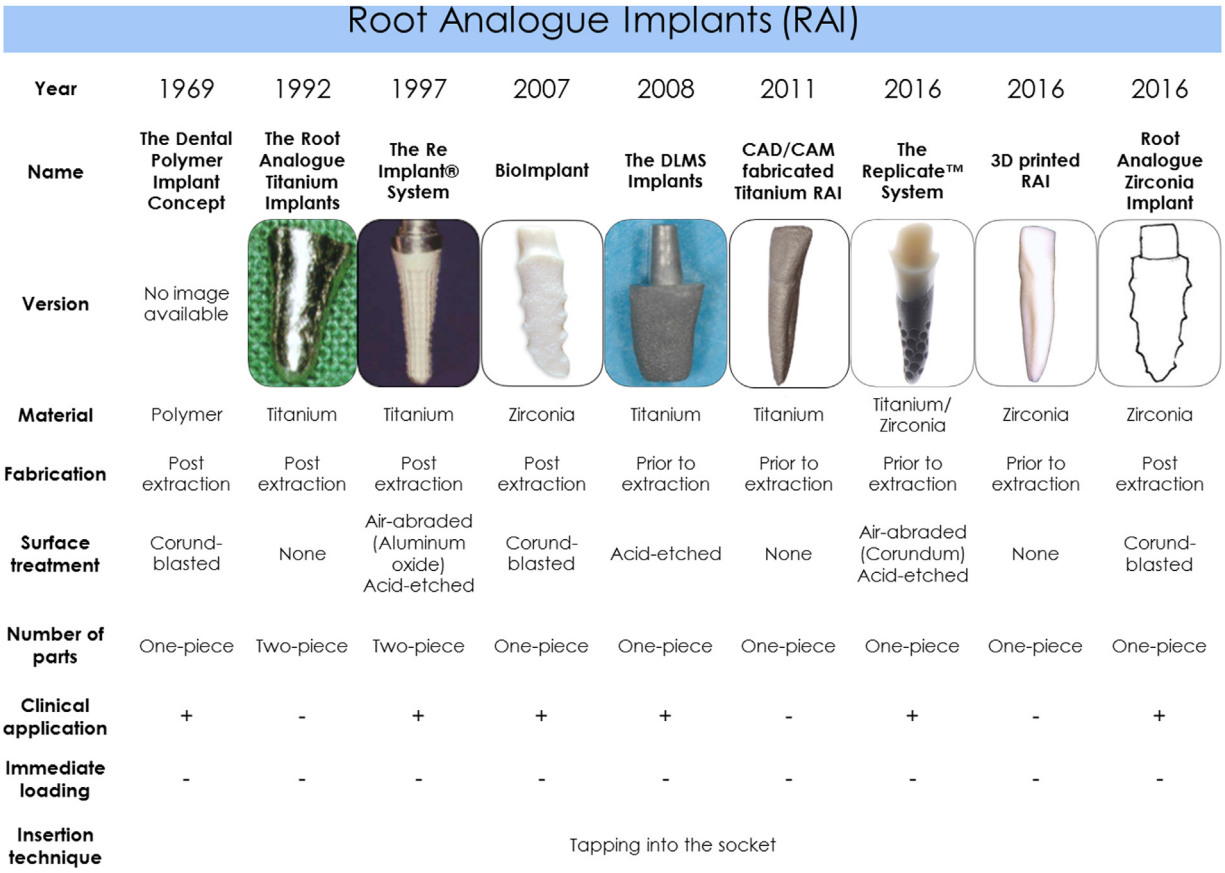

Fig. 1. Diagram of root analogue implants since the beginning of their development until today.

copying process was done according to the technique described in 1989[19] and combined the spark erosion with a method of machine duplication for fabrication of the crown, which eliminated the inherent errors that resulted from waxing, investing, and casting.[19] After the fabrication, the implants were cleaned manually and ultrasonically in N-butanol for 15 minutes, and then in graded series of ethanol (70%-99%) for another 15 minutes, and sterilised in an autoclave at 135 °C for 20 minutes. With the longer fabrication process, the implants were then installed two weeks after the extraction by making a ridge incision, followed by mucoperiostal flaps to expose the sockets. The intra-alveolar soft tissue in the healing phase had to be removed and the root analogue implants were put in place.[13]

It was possible to conclude from clinical and histological findings that the titanium root analogues osseointegrated with a high degree of predictability when implanted into extraction sockets during an early stage of healing.[13] The authors found an osseointegration rate of 88% and noticed that a good fit between the implant and host bed was an important factor for success. For this reason a new approach to inserting the implants by widening the coronal area to compensate for the lost periodontium and achieve good congruence between the implant and the extraction socket was refined in 1997.[20]

The ReImplant® system

In 1997, a new model was introduced, and initially tested in monkeys. [20] The extraction was by means of buccal and palatal full thickness flaps and the root of the extracted tooth was scanned extraorally with laser. The data obtained were transferred to computer software where a design modification was made on the coronal part of the implant analogue, which was slightly enlarged circumferentially to promote better adaptation and obtain a good congruence between the implant and the extraction socket.[20] The milling unit then fabricated the implant from a cylindrical titanium blank according to the computer data.

The surface treatment of the root involved air-abrasion with aluminum oxide powder (500 μm) and acid etching, while the entire part above the alveolar bone was polished. The implantation was inserted six to eight hours after extraction, and the authors reported that the volume of some implants was too great to fit into the respective extraction socket, which led to fractures of the thin buccal alveolar wall. This minimal difference in volume could be related to the first generation of the laser-scanner and the milling unit that were used to fabricate the ReImplant® System.[20] The fit of the implant without macroretentions might be responsible for the failure in the intermediate term, which was the

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result of pressure-induced resorption.[1] A case report from 1997 described the use of this technique to replace an upper lateral incisor, and the authors highlighted the simplicity of the procedure, the possibility of maintaining the aesthetic interdental papillae, and the advantage of shaping the natural design of the root, but they also recommended further basic and clinical research before recommending the system for use by private practitioners.[16]

The BioImplant™

In 2007, the BioImplant™ was described as a new design for root analogue implants, using zirconia as the material from which to fabricate the implant for advanced biocompatibility and improved aesthetics.[21] Microretentions and macroretentions were added to the entire root surface to improve primary stability and therefore osseointegration. In this new design, the diameter of the implant next to the buccal cortical bone was reduced in an effort to avoid fracture of the bony wall and pressure-induced bone loss.

The tooth was extracted, the socket curetted, and an iodoform-soaked cotton gauze was placed in the extraction socket. The root was scanned with laser, macroretentions were designed, and a crown stump was created for later connection to the crown. The implant was milled from a pre-sintered zirconium dioxide blank and sintered into the final stage and size for eight hours. The surface was roughened by abrasion with airborne particles. Four days after extraction, the implant was placed into the socket by finger pressure and subsequent gentle tapping with a hammer and a mallet.[21] In 2009, this type of implant was used to replace a molar in the upper jaw[22] and a right lateral maxillary incisor.[23] At two years follow-up, all variables had successfully been met. The last two cases using the BioImplant™ were reported in 2016 to replace a first premolar and a first molar.[24]

Direct laser metal sintered (DLMS) implants

DLMS implants were first described in 2008[25] using the cone-beam CT data and CAD/CAM technology for the direct production of custom-made root analogue implants in a biocompatible titanium alloy.[26] This technique involved a high-power laser beam focused on a metal powder bed and programmed to fuse microparticles according to a CAD-file, to build the desired object layer-by-layer.[26,27] The implants and integrated abutments were produced from DLMS technology (Leader Implants) from Ti-6Al-4 V alloy powder with particles ranging between 25 and 45 μm in size.[25–28] Surface treatment was by etching with acid through the immersion of the sample in a mixture of oxalic acid (50%) and maleic acid (50%) at 80 °C for 45 minutes.[26] This implant was fabricated from cone-beam CT data before extraction, so by the time of extraction the implant could be inserted in the socket by finger pressure or tapping. Primary stability of the implant was checked by palpation and percussion. Provisional crowns were cemented on the custom-made abutments.[26] The radiographic fitting control at the one-year follow-up gave a survival rate of 100%. However, the authors recommended that when an atraumatic extraction is not possible, or if there is loss of any alveolar bony wall, the use of this type of implant should be avoided and standard implants used. Divergent roots were also a limitation.[26]

A new method of digital laser metal forming (DLMF) was reported in 2012 in humans. The DLMF technique allows the fabrication of functionally-graded titanium implants with porous surfaces, which may provide better adaptation of the load. [28] These studies highlighted that DLMS/DLMF implants were successful and had the main advantage of being fabricated before extraction, making immediate placement of the root analogue implant possible.[28]

CAD/CAM fabricated titanium root analogue implants

A new method of creating single-rooted titanium root analogue implants was described in 2013 that also combined cone-beam CT 3-dimensional acquisition of data with CAD/CAM technology.[29] This was described on a dead human body, and the selected tooth was a lateral lower incisor. First, the mandible was scanned and the data exported in DICOM format. Three-dimensional surface models of the tooth were created, and the implant was fabricated using high-end selective laser melting, by depositing and melting thin layers of metal powder from a biocompatible titanium alloy (Ti6Al4V). Optical scanning was used to check the accuracy of the manufactured titanium implant related to the cone-beam CT 3-dimensional root surface, and good precision manufacturing of the implant was achieved. No changes were made on the surface of the root. For this reason, the authors reported that this implant would not have sufficient primary stability after placement. It was suggested that macroretentions or microretentions should be added, and the surface treated, to give better primary stability and osseointegration.[29]

The Replicate™ *tooth system*

In 2016 a case report described a new technique for the fabrication of a root analogue implant through CAD/CAM technology.[15] A cone-beam CT and elastomeric or digital impressions were necessary to produce both the root and the coronal part of the implant. This implant can be fabricated before extraction and is composed of a titanium root and a zirconia (3Y-TZP) abutment that are fused together by a sintering process that generates a one-piece hybrid implant. This procedure avoids there being a microgap between the root part and the abutment and reduces the bacterial colonisation in this sensitive area, which has been reported to cause bone and soft tissue loss.

To fabricate the "Replicate™" tooth, impressions were made and a cone-beam CT taken. The data to be used to

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calculate the dimensions of the implant were sent to the manufacturer (Natural Dental Implants AG) so that an individual implant could be fabricated. The CAD procedure consisted of obtaining the data from the image, and the CAD process. The cone-beam CT 3-dimensional data are received in a single DICOM file format, with the data for impressions or intraoral scans in an open STL file or CEREC format. The impressions are then digitalised by a micro-CT device and the surface reconstruction of the natural shape of the root and adjacent alveolar bone contours is initiated. At this moment, the dentists can send their prescriptions, preferences, and treatment plan. The authors of the case report described,[15] opted to design the implant with an intentional reduction of the coronal part (first 4 mm of the root) on the buccal side to avoid pressure on the thin buccal wall of the socket and to provide space for augmentation of the bone.

The computerised prototype of the Replicate™ tooth system is created, root anomalies and divergences are corrected, the insertion simulated, and the interproximal spaces adjusted. The desired shape, position, and inclination of the crown are then also adjusted. The interface between the titanium root and the zirconia abutment is defined virtually, and a widening of the root is designed in a mesiodistal direction to make it possible to achieve good primary stability after insertion. The components of the Replicate™ tooth system are then prepared for glass soldering; the zirconia abutment is fused to the titanium root with biocompatible glass solder, and the one-piece hybrid material replicate implant is generated. The margins of the abutment are polished with medium abrasives (100 and 40 μm grain size),[30] while the titanium root portion is abraided with medical grade corundum and etched to create micrometered roughness for optimising osseointegration. A micro-CT device is used to measure the dimension of the glass solder interface, and ensure that the microgap between the implant and the abutment is avoided. The implant is inserted by gently tapping it into the socket. To protect the replicate tooth during healing, a cover shield (a temporary one-wing adhesive zirconia bridge) should be fixed to the adjacent tooth.[15] Fig. 2 A and B illustrate the process of obtaining the Replicate™ tooth from planning to the final product.

Three-dimensional printed root analogue implants (future perspectives)

Although titanium is a successful material for fabrication of implants it can cause hypersensitivity and corrosion because of gradual degradation of the material.[31–33]Zirconia has therefore been proposed as an alternative, as it has better biocompatibility and aesthetics, and is more resistant to corrosion.[33] When these characteristics were combined with the innovations of 3-dimensional printing, it became possible to fabricate a 3-dimensional printed zirconia root analogue implant using digital light processing technology, which was first described in 2017.[33]

This is an additional manufacturing technique (Rapid Prototyping) in which solid 3-dimensional objects are built using a digital light processing projector to translate voxel data, and it is similar to the previously described method to print titanium implants[27] (DLMS implants) by which specific geometry is built up layer-by-layer. The images were obtained by cone-beam CT, processed, and converted to a 3-dimensional surface model using the marching cube algorithm and saved in the standardised triangulation language (STL) file format. A printable 3-dimensional implant was then reconstructed using CAD software and the fabrication made using the high-end digital light processing, 3-dimensional printing technology. The congruity of the printed zirconia implant compared with the CAD model of the implant and the optical scan of the natural tooth, was checked by superimposition. The authors highlighted that this experiment was a first step to 3-dimensional printing of individual zirconia implants. However, some divergence was noticed in the apical area between the scan of the printed implant, the CAD model, and the optical scan of the natural tooth.[33] This showed that digital light processing 3-dimensional printing technology results in less accurate fabrications of implants than the commercially available additive manufacturing techniques for metal such as DLMS.[26,33] The authors concluded that it is feasible to print a 3-dimensional zirconia implant. However, possible surface modifications would influence the osseointegration, and the peri-implant biology needs further investigation.[33]

Root analogue zirconia implant (future perspectives)

A new method to fabricate root analogue zirconia implants was described in 2016.[34] In this design the surface of the root was modified in two ways: first, microretentions were added to the entire root surface, and macroretentive steps were added only in the mesiodistal root surfaces. The diameter of the implant was then reduced next to the thin cortical alveolar bone to avoid both fracture and pressure-induced bone loss. The implant was used to replace a first premolar. The tooth was then extracted and the socket cleaned. The root was modified with light-cured composite material to create a post (abutment) to receive a further crown. The macroretentions were designed, and the modified root was scanned with laser. The replica was milled by CAD/CAM technology and the surface treated with abrasion with airborne particles and pre-sintering; the zirconia implant was then sintered into the final size over eight hours. Three days after extraction, the implant was placed in the alveolus by finger pressure and subsequent tapping with a special hammer and a mallet; primary stability was confirmed by palpation and percussion. Definitive restoration was possible after four months. The follow-up at 18 months showed that the implant was stable, the level of the implant marginal bone was unchanged, and complete apical peri-implant ossification was apparent on radiographs.[34]

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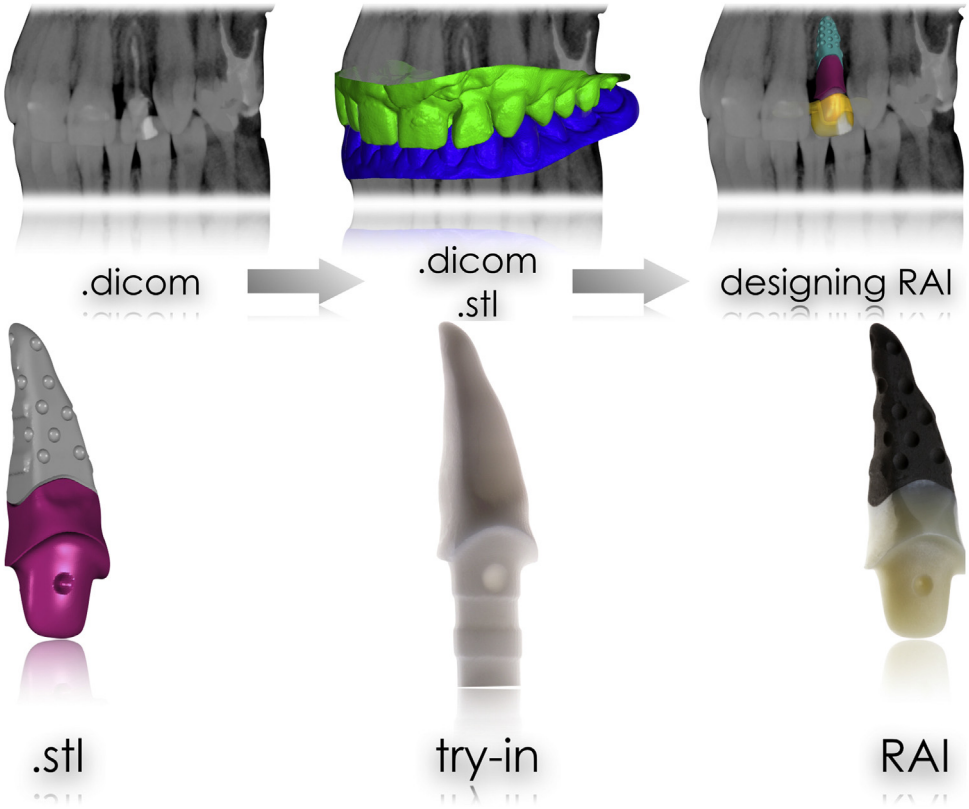

Fig. 2. (A) and (B). Process of obtaining the replicated tooth implant - from the planning to the final product.

Discussion

According to these published papers it is evident that tooth loss predominantly leads to resorption of bone and soft tissue.[4] Immediate implantation in the post-extraction socket might reduce, but not avoid, these alterations to the ridge.[1–8] In addition, the operation of immediate implantation with conventional implants can be difficult for the operator. To achieve primary stability, the bone drilling will normally need to exceed the apex of the socket in 4-5 mm,[11] which will require a larger quantity of bone that might not be available or might be closely related to vital structures such as the inferior alveolar nerve or the maxillary sinus.[35] The available bone in a post-extraction socket is often infected, or poorly vascularised, or both.[11]

Controlling the three-dimensional position of the implant is challenging, because it is a symmetrical object that is being inserted into a non-symmetrical socket with variable morphology.[11] The surgeon's experience is therefore important in the 3-dimensional positioning of the implant, which might be placed too deep or too buccal in the socket, which would lead to functional and aesthetic problems.[8] Another difficulty is the incongruence between the sizes of the implant and the extraction socket that, after placement of the implant, may lead to connective tissue or epithelial growth around the parts of the implant that are not in direct contact with the bony walls. To prevent this, the use of barrier membranes or bone augmentation between the implant and the socket walls is recommended.[20,36] An additional limitation is the cylindrical design of conventional implants that requires preparation of the socket with drilling burrs, which could overheat the bone and lead to damage that might affect osseointegration.[37]

The use of root analogue implants could be an alternative to improve results with immediate implantation, as the patient's individual replicate implants have the same design as the natural root, which might reduce the difficulties previously cited when using conventional implants. This technique was described for the first time in 1969[12] and, over the years, several types of implant have been developed. The ReImplant® system, however, was the first one to have a modified root design.[16,20]This modification was important to show that changes in volume at the root of an implant might result in better osseointegration with a better fit of the implant into the alveolar socket.[20] Conversely, the enlargement of the coronal part of the implant often led to fractures of the buccal wall, and a study showed both excellent primary stability on the one hand, and a highly disappointing failure rate of 48% at nine months follow-up on the other.[38] The high failure rates led to further modifications of the surface, which improved the fit of the implant without generating pressure on the bony wall.

One study described the need to reduce the area that is in contact with the buccal bony wall by 0.1 - 0.3 mm, because this might avoid pressure-induced bone loss.[39] Another fun-

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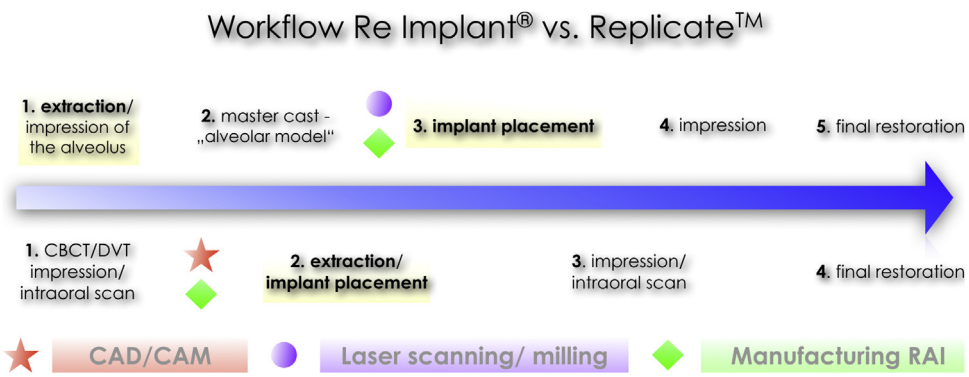

Fig. 3. Overview of the differences between the systems "Re Implant" and "Replicate Implant" according to fabrication method, time of placement, and final restoration.

damental influence on the success of immediate implants regardless of the type of implant being used is the thickness of the buccal bone at the moment of implantation. Spray et al[40] reported a study of more than 3000 implants, and evaluated the thickness of the buccal plate during implantation and the second stage of the operation (uncovering). They found a small but not significant difference between the successful implants and the ones that failed (0.1 mm less bone thickness). However, a pattern of favourable changes in the response of buccal bone, with bone gain after the healing period, was found in the implants that had bony thicknesses close to 1.8 and 2.0 mm. The authors considered 2 mm as a "critical thickness" to be available around the implant and that, when the buccal plate is less than 2 mm, more bone loss should be expected during remodelling.

This is even more important in the case of immediate placement of implants, as no preparation of the socket is needed. The thickness of the buccal wall is therefore the one that was present around the original tooth before extraction. A carefully and minimally invasive extraction is therefore necessary to preserve bone and, in the case of less than 2 mm thickness, the surface of the implant should be reduced to provide space for a bone graft.

The addition of microretentions or macroretentions was also reported to improve the desired osseointegration.[15] The application of the cone-beam CT and digital technology to the designing process allows the system to place the retentions in areas of thicker bone. In the areas of thinner bundle or interdental bone, pressure is avoided by the reduction of the dimensions of the implant (as mentioned before) and also by allowing space for selective bony augmentation to counteract any bony resorption of these areas. An individual implant can therefore be designed, taking the remodelling processes into consideration.

The advanced use of digital technology such as the CAD/CAM systems combined with cone-beam CT allows fabrication of a root analogue implant before tooth extraction, and enables the placement of the individual implant immediately after extraction.[15,39] This technique avoids additional intervention. Fig. 3 summarises and compares the necessary treatment steps both for the modern Replicate™ tooth system and the ReImplant® system. The treatment time of the Replicate™ tooth system is clearly less than that with the ReImplant® system (four rather than five interventional steps). As well as the reduced treatment time, another advantage of the Replicate™ system is that it is a hybrid implant, composed of a titanium root directly fused to a zirconia abutment without any microgap that could cause loss of bone and higher failure rates.[15] This version of a root analogue implant can be fabricated before extraction with the aid of modern cone-beam CT and CAD/CAM technology, which results in an individual root analogue for the patient, designed and fabricated in a short period of time. In the ReImplant® system, an impression of the extraction socket after extraction of the tooth is needed for further fabrication of the implant, which results in a second intervention to insert the ReImplant® implant. This is harmful to the ongoing healing process and could lead to reduced success rates.[16]

Although titanium is widely used for manufacturing dental implants, its dark colour can become visible in some cases, which causes a greyish discolouration in the patient's mucosa, particularly in the aesthetic zone.[14,41,42] The zirconia abutment of the Replicate™ implant offers a better aesthetic result without compromising the resistance of the set, as 3Y-TZP-zirconia has excellent mechanical properties (flexural strength >1000 MPa).[43]

The Replicate™ implant also has its surface treated by acid-etching, which consists of increasing the thickness of the oxide layer and the surface roughness by immersing the implant into an acid solution (hydrofluoric acid), which erodes the surface and produces micropits. This provides homogeneous roughness, increases the active surface area, and improves cell adhesion.[15]

There is increasing concern in implantology about aesthetics, biocompatibility, and the corrosive behaviour of materials. Root analogue zirconia implants are becoming a good option because they favour aesthetics even in the presence of a thin buccal wall or gingival biotype, are resistant to corrosion, are hypoallergenic, and are bioinert.[44] Additionally, studies done with the finite element method have shown that zirconia implants produce higher stress values on trabecular bone, and so protect cortical bone. Conversely, zirconia

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implants have a smoother surface than titanium implants, and surface treatments are still limited for zirconia implants, particularly because of the chemical resistance of zirconia surfaces. This might limit its osseointegration potential when it is compared with titanium. Although the difference in osseointegration and bone-to-implant contact was reported as not significant, studies are focussing in new modifications of the surface to improve osseointegration of zirconia implants and its consequences in the materials' mechanical behaviour before use.[44]

Several different types of implants have been described over the past decades, which were fabricated in different conventional and industrial ways with diverse material compositions. Yet most of them remain in the past and contributed to the technique being rejected because of high failure rates or difficulties in the fabrication process. It is important for the dental team to have a detailed overview of root analogue implant systems to be able to choose if one will be able to fulfill aesthetic and functional requirements in specific cases, combined with having a simplified and time-saving fabrication process.

The implant procedure is technique-sensitive, and should be used only with adequate experience. More evidence-based data from prospective, long-term, clinical studies, however, are necessary to give a better evaluation of the systems available.

Ethics approval and patients' consent

Neither was required.

Conflict of interest

We have no conflicts of interest.

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