Bio-replication: Foundation, Form, Function Engineering Predicates for Successful Rehabilitation of Natural Teeth and Bio-mimetic Replacements

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Two biologic absolutes relate specifically to the foundational pillars of reconstructive dentistry; the dental pulp is the ideal root filling material, and the ideal implant is the periodontally sound and clinically intact tooth. A myriad of pathologic and technical vectors contravene the attainment of either absolute; however, retrospective cross-sectional population studies comparing initial non-surgical endodontic therapy and single tooth implants show similar, albeit miniscule failure rates.[1,2] It is in the realm of restoration that dichotomies appear, particularly in treatment sequencing.

In the case of the single tooth implant, if the treatment planning sequence proceeds from biology to structure, then to function and subsequently to aesthetics, the resultant aesthetic outcome may well be compromised. Therefore, the process need transpire in the opposite direction; the treatment planning process is initiated with aesthetics and proceeds to function, structure and finally, biology.[3,4] In the case of the natural tooth, treatment sequencing is the reverse.

There is considerable confusion between what constitutes standard of care for the endodontically restored tooth and the implant restored fixture

Biologic width is the measurement of junctional epithelium and connective tissue attachment on the root surface of a natural tooth; it is calculated to be 2.04 mm[5-7] (Fig. 1). It is difficult to restore a tooth to the precise coronal edge of the junctional epithelium; thus in addition to the roughly 1mm depth of the sulcus included together with the biologic width, allowance must be made for a 0.5mm safety zone between the margin and the coronal portion of the epithelial attachment. Variability in the height of combined epithelial and connective tissue attachments has been reported as between 1.5 and 4.5mm[8] which suggests that at the very least, approximately 4mm of tooth structure must be above the osseous crest for a successful restoration. If these considerations are not taken into account and the biologic width is violated, three things tend to occur; chronic pain, chronic inflammation of the gingiva, and unpredictable loss of alveolar bone (Figs. 2A-C).

There is considerable confusion between what constitutes standard of care for the endodontically restored tooth and the implant restored fixture. Most implant systems accept osseous die-back of 1.5 to 2mm from the connection interface between the abutment and the fixture. This "remodeling" of the osseous crest and creation of a soft tissue attachment is referenced as biologic "height".[11,12] It's effectiveness against toxic ingress is dubious as in the absence of a definitive and stable bony base, the soft tissue "seal" is subject to inflammatory instability. If a biologic seal is paramount in the natural scenario, then the bio-mimetic surface and design, collar configuration and abutment shape should seek to optimally replicate the natural state with no inflammation of the peri-implant hard and soft tissue, no progressive loss of the peri-implant bone and no progressive loss of the peri-implant mucosa.[13] This article will address the engineering predicates for successful rehabilitation of the endodontically treated tooth and the osseo-integrated implant fixture, their similarities, differences and intersection.

Successful rehabilitation of root-filled teeth mandates an effective coronal seal, protection of the residual tooth structure, restored function and optimal aesthetics. A post/core retained crown may be indicated to fulfill these requirements; however, failure of the post/core restored tooth due to root fracture is not an uncommon consequence. Therefore, crown and post/core preparation design features that reduce the chance of root fracture would be advantageous.[14,15]

A ferrule is a circumferential metal ring or sleeve placed around a slender shaft to strengthen it or to act as a casing for holding a tool. A dental ferrule or perhaps more aptly named, a dental collet, is an encircling band of cast metal around the coronal surface/root face of the tooth. The use of a ferrule as part of the core or artificial crown may be of benefit in reinforcing root-filled teeth by containing and redirecting forces within the remaining structure of the root. A protective effect occurs owing to the ferrule resisting functional lever forces, the wedging effect of tapered posts and the lateral forces exerted during occlusal torquing and/or excursive function.[16] A dynamic balance between the ferrule length obtained and the remaining root is therefore needed (Fig. 3).

Joseph and Ramachandran evaluated four groups of extracted teeth; 1 and 2mm of residual facial dentin with and without a 60 degree bevel as their experimental design and concluded that the use of a 2mm collar increased the resistance of the tooth to root fracture.[17] These findings have been replicated by several investigations, each demonstrating as well, that enlargement of the canal shape beyond that developed during instrumentation should be kept to an absolute minimum.[18-20] There is an emerging consensus that in addition to the preservation of as much coronal tooth substance as possible, a butt-joint margin (minimal taper) between the core and tooth should be used. The ferrule or collet effect should incorporate a 360 degree metal collar of the crown surrounding the parallel walls of the dentin extending coronal to the shoulder of the preparation.[21] The result is an elevation in resistance form of the crown from the extension of dentinal tooth structure (Fig. 4).

If unpredictable bone loss and inflammation is to be avoided, the crown margin should be at least 2mm from the alveolar crest

Basing their study on this effective ferrule design, Libman & Nicholls investigated the influence of ferrule length on resistance to preliminary failure.[22] The authors defined preliminary failure as the propagation of a crack in or around the luting cement of the crown. Twenty-five extracted maxillary central incisors were split into five groups; a control group and four test groups. The test groups had ferrule lengths of 0.5, 1, 1.5 and 2mm. The teeth were prepared with 1 mm wide shoulders. The test teeth had cast post and cores cemented and the control group did not. All the teeth were restored with cast crowns.

The teeth were subjected to cyclic loading until preliminary failure was detected, using a strain gauge on the root and crown interface. The goal was to count the number of cycles that produced marginal opening. By evaluating the results between groups with different ferrule heights, a sense of how much residual tooth structure is necessary could be determined. The control group and the teeth with 1.5 and 2mm ferrules were found to be significantly better than the teeth with 0.5 and 1mm ferrules in resistance to preliminary failure. The authors concluded that 1.5mm should be the minimum ferrule length when restoring a root-filled maxillary central incisor with a post/core-retained crown.

As referenced earlier, the ferrule length is influenced by the biologic width. If unpredictable bone loss and inflammation is to be avoided, the crown margin should be at least 2mm from the alveolar crest. It has been recommended that at least 3mm should be left to avoid impingement on the coronal attachment of the periodontal connective tissue.[23] In those clinical situations where there is insufficient ferrule length, even where margins are placed subgingivally, the clinician may consider surgical crown lengthening or orthodontic extrusion. This allows the distance between the crown margin and alveolar crest to be widened and increases the potential ferrule length.

The restoration of endodontically treated has become increasingly conflicted in the adhesion era; what are the impact of endodontic irrigants on the molecular properties of dentin, what is the impact on the proportional limit (in compression), the modulus of elasticity and the ultimate strength in compression and tension of the dentin residual in teeth with root fillings. The issues of bond strength especially as it relates to glass fibre posts and their fatigue resistance warrants continued study as the results in the literature are confusing. Their performance in vitro approximates that of metal posts and most studies agree that their failure mode is more favorable than with metal posts. Clinical studies have been favorable to date. The use of fibre posts will continue to grow, assuming that long-term clinical research studies report similar levels of success as seen in the relatively short-term studies already published. Further modifications of their physical and mechanical properties will probably also improve their clinical performance. Their value will be further enhanced if little or no repreparation of the post channel is required to place them.[24]

As an integral component of rehabilitation, post channel preparation and post material and design must be factored into the algorithm of restorative success. Based on numerous investigations, if certain basic principles are followed in the restoration of endodontically treated teeth, it is possible to achieve high levels of clinical success with most of the current restorative systems. These principles include; avoidance of bacterial contamination of the root-canal system, the provision of cuspal coverage for posterior teeth, the preservation of radicular and coronal tooth struc-

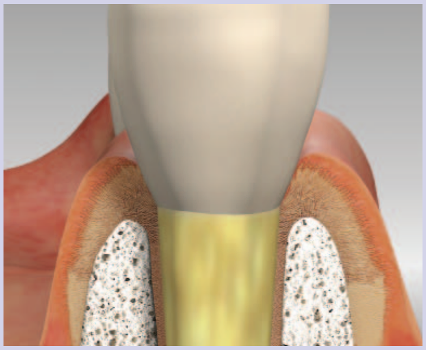


FIGURE 1—Biological width refers to the height of the dento-gingival attachment apparatus around a normal tooth and is defined as the distance necessary to create a healthy co-existence of bone and soft tissue from the most apical extent of a dental restoration. In a more clinical sense, the definition states that there must not be any encroachment of a restorative margin within two millimeters of the bone that surrounds the tooth.

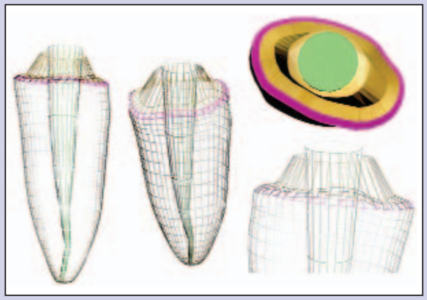
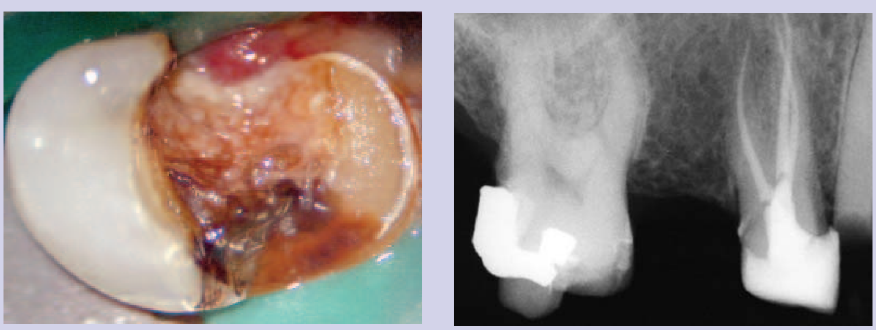


FIGURE 2A—A dowel is a pin, usually made of wood, plastic or metal, used to secure two objects together. The dowel reinforced butt joint or simply dowel joint has been a very common method of reinforcing butt joints in furniture for centuries. The holes are drilled such that there are corresponding holes in each member into which short dowels are inserted with some glue. The joint is brought together and clamped until the glue has dried. This produces a joint which is much stronger than a butt joint without reinforcement. The dowels offer some holding strength even after the glue has deteriorated. Over time, dowels may shrink and become loose. They take on an oval shape in section owing to the different rate at which wood moves with different orientations of the grain (Source — Wikipedia).



FIGURES 2B & C—The coronal tooth structure of this bicuspid has been lost to caries. Even though the structure has been replicated subsequent to the root canal procedure, occlusal forces will serve to unseat the restoration as the bond at the tooth/restoration interface deteriorates over time.[9,10] The fracture resistance of endodontically restored teeth is dependent on the degree of tooth conservation. An incomplete crown ferrule is associated with greater variation in load capacity and, despite high fracture values, will still be inclined to fracture. An adequate bulk of tooth coronal to the restoration margin is required to restore the tooth. The amount of coronal tooth structure, along with the position of the tooth in the arch, will dictate the type of build-up indicated, whether a preformed post, or a cast post and core are indicated and whether a crown is needed.

ture, the use posts with adequate strength in thin diameters, the creation of adequate post length for retention with sufficient residual obturation material to ensure an undisturbed apical seal, and posts that are retrievable (Fig. 5).

However; adhesive trends will not obviate the need for a circumferential ferrule, nor will they circumvent the necessity for optimal biologic width to ensure a healthy attachment apparatus. Adhesive cements will not bio-chemically immobilize ill-fitting crowns or ensure marginal retention to inadequate surface dimensions. The need for intimacy of fit, the absence of leakage, and an unyielding response to stress and torque apply equally to both the endodontically treated tooth restoration and the implant supported restoration. The expectations should not vary nor be excused based on a differential in material or design. Leakage, occlusal disharmony, off-angled forces and their injurious impact and micro-pumping at an interface are not well tolerated by the host organism under any circumstances.

It is increasingly apparent that the ease of restoration of an implant fixture is inherently more simplistic and predictable than the rehabilitation of a natural tooth. The simpler the restorative system used, theoretically, the more facile and reliable the restorative process. This may well apply to the full or partial reconstructive scenario; however, single tooth replacement with osseo-integrated fixtures brings with it an entirely new set of bio-mimetic

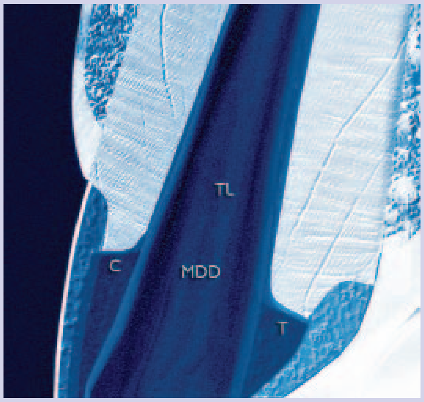


FIGURE 3—C – compressive forces under function, T — tensile load under function, TL — torque load — area affected most by removable and/or fixed partial denture loading, MDD — mesio-distal dimension — narrowest root dimension and thus the weakest in a bending load.

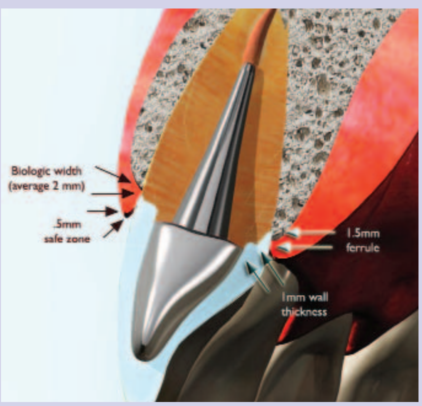


FIGURE 4—There are several key elements that facilitate an ideal restoration. A facial and lingual ferrule must be present with dentin walls minimally 1mm in thickness. The post/core's resistance to compression and the ferrule's resistance to tension mandate dimensions as indicated in the diagram. Ideally, 4mm of tooth above bone is necessary for a patient with an average attachment height to achieve a ferrule of 1.5 to 2mm with a biologic width of 2.0mm and a safe zone of .5mm.

FIGURE 5—Initial clinical studies of fiber post systems seem promising, but longer-term follow-up is necessary to determine whether having a flexible post allows movement of the core, resulting in increased microleakage under the crown, especially when restoring teeth with minimal remaining tooth structure.

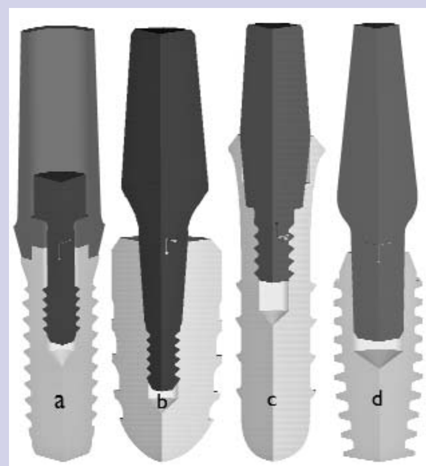


FIGURE 6—Various implant-abutment attachment methods — **A**) NobelBioCare, **B**) Ankylos, **C**) ITI, **D**) Bicon. The TIS type abutment (Ankylos and ITI) offers a high resistance to loosening torques in single tooth replacements. This is particularly significant in regard to the insertion force, the ratio of the pull-out force to insertion force, and the critical insertion depth. A multicentre retrospective study of 74 single implants investigating the success rate of the ITI implant system showed a 3.6% loosening of the implants in a six month followup whereas none were encountered with a similar cohort from the Ankylos implant system.[28-30] Images used with permission from Bozkaya and Mufti.

requirements. Mixing natural teeth and their fibrous ligamentary attachment with implant fixtures and their titanium-oxide interface mandates an occlusal accuracy and axial orientation specificity previously marginalized in rehabilitative therapy. The axial component of the occlusal force is predominantly compressive for a single tooth restoration. However, for multiple tooth restorations that for example support a bridge, the axial component of the occlusal force could become tensile with a magnitude as large as 450 N [m.kg.s-2].[25] The design of the implant-abutment interface must consider these loading mechanisms.

In addition, the reliability of the abutment retention mechanism design, the screw, the tapered interference screw (TIS) or the purely tapered interference fit (TIF) adds yet another variable to the observed modes of implant complexity and complications. The focus has shifted from the "surface" that produces optimal osseous integration to the connection of the implant fixture with components that are immobile within their housing and at the collar/platform interface to negate traditional inflammatory responses invariably associated with hex/screw connections. Inadequate screw preload, the misfit of the mating components and rotational characteristics of the screws are considered to be the reasons leading to screw loosening or fracture.[26] In the TIS (b, c) and TIF (d) abutments, the connection is secured by the frictional forces on the screw threads and on the tapered section. Depending on the design, the contact area and the contact forces on the tapered section of the abutment are considerably larger as compared to those of the screw threads. Therefore, most of the resistance to loosening torques occurs in the tapered section[27,28] (Fig. 6).

Historically, the deleterious consequences associated with micro-gaps (micro-pumps) were tolerable in areas where emergence profile was inconsequential or aesthetics of little or no concern. However, where implants are adjunctive, ancillary or integral to the foundation, form and functional needs of the prosthesis, this by necessity has to be eliminated (Fig. 7).

Biologic width around an implant is apical to the fixture/ abutment connection, one of the reasons that maintaining or reforming a papilla between two implants presents with such difficulty.[32] Only very recently has the trend been to position a "flat fixture platform" equal to or below the interproximal or inter-implant bony crest.[33] This places biologic width genesis sub-crestally as well, however, the interface must be designed to prevent bone die-back and associated gingival recession.

These deep profile systems need careful development of the shape and height of the soft tissue complex during provisionalization

Thin-scalloped or thick-flat periodontal biotypes impact on papillary maintenance as well. Treatment planning for a reconstructive prosthesis integrating natural and bio-mimetic foundations mandates a skill set in orthodontic tooth movement to force eruption,[34] hard tissue grafting (sinus lift, ridge augmentation), splitting techniques and distraction osteogenesis. Esthetic failure, in which the implant and prosthesis are intact, but the patient's needs have not been met is as consequential as complete loss of the implant.

The collar design (Fig. 8) that defines the shape of the abutment/fixture interface determines the quality of the soft tissue attachment as well the osteolytic impact of hygiene and function on crestal bone levels. If the design enhances the integrity and definition of the junctional tissue attachment, then the biologic brunt borne by bone diminishes and crestal regression lessens. The fibrosity and turgidity of the soft-tissue attachment must be optimized to prevent peri-implantitis and other pathology from impacting on the inter-implant or inter-radicular osseous support. The configuration of an emergence profile that emulates nature's design is paramount in terms of aesthetics, health and permanence. The ideal design parameters that achieve this objective will be addressed momentarily.

Implants that have built-in collars designed for soft tissue attachment do not require placement of the implant platform below the crest of the bone. Placement at or apical to the osseous crest produces a deep profile restorative dilemma where the soft tissue complex needs considerable time to reorganize because bone resorption must occur first. These deep profile systems need careful development of the shape and height of the soft tissue complex during provisionalization. Even when mature, these soft tissue complexes readily tend to bleed and collapse. The reason for this negative effect is solely related to the comparable size of the abutment / fixture interface.

Implants that are not positioned below the osseous crest tend to have shallow emergence profile characteristics that require little or no augmentation of their contour and are theoretically, much simpler to deal with restoratively. However, bone loss is typically 1.5mm to 2mm apical to the abutment/fixture connection with this design configuration. The hard tissue remodeling and resultant soft tissue attachment is accepted as the means by which the biologic height is achieved.[36] The impact on the development of the biologic dimension established by the vertical repositioning of crestal bone and the subsequent soft tissue attachment to the implant that occurs when an implant is uncovered and exposed to the oral environment is expected and readily evidenced radiographically (Fig. 9a). Again, this is most demonstrable with matching diameter restorative components.[37] This issue of establishing idealized, sustainable, predictable biologic width is simply not being addressed as the relevant archetype or is marginalized by altering the size of the restorative component with platform switching or "shifting."[38]

Compensatory downsizing of the restorative abutment by platform switching or shifting is simply an accommodation necessary to obviate flaws in the design of the interface connection. These configuration adaptations still fail to fully address the biologic width imperative so integral to the aesthetic zone. The euphemism "bone sets the tone" should be reflected in pre-made components that take into consideration the variation and imprecision of a natural order rather than having to rely on customization in order to accommodate eccentricities. Indeed, using the principles outlined above, the restoration of implants can be simplistic and engender idealized biologic width in both horizontal and vertical directions. The impact on the post-restorative biologic process resulting in the loss of crestal bone height can be altered when the outer edge of the implant-abutment interface is horizontally repositioned inwardly and away from the outer edge of the implant platform (Fig. 9b).

This raises the question as to why hex connections remain an implant design feature at all. An ideal fixture design would consist of a body configured with a progressive thread structure for targeted load distribution to the spongy bone of the apical extent and a gap-free sub-gingival tapered connection to the abutment. The length or slip of the restorative component over a hexagonal fixture head, and the length of the tongue and screw component passing into the secondary component of the body need be 1mm or more to effect a definitive seating engagement. In this design, a gap-

FIGURE 7—These µCT images show that micro-gaps at the implant-abutment interface can engender adverse effects. These including screw loosening, abutment rotation, abutment fracture and peri-implantitis. Interface gapping/pumping is reported to be associated with progressively negative biological changes and the continuous mobility between components imperils wound healing around the implant. Tissue response induced by inflammatory vectors can be as aesthetically disastrous as that induced by impingement on the biologic width in the natural tooth scenario.

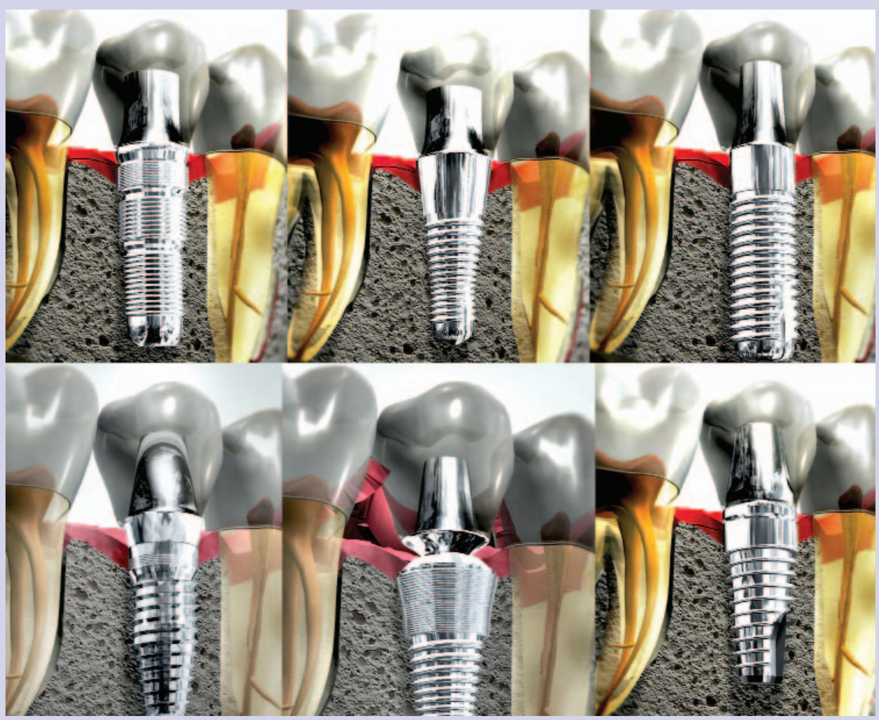


FIGURE 8—The location of the interface (micro-gap), when positioned at or below the alveolar crest, determines the degree of crestal bone resorption. These changes are dependent on the surface characteristics of the implant as well (machined or rough) and the presence/absence as well as the location of an interface (micro-gap). A rough surface with micro-threads at the implant neck is the most effective design to maintain the marginal bone level against functional loading.[34]

FIGURE 9A—Loss of bone apical to a hex configuration fixture/abutment connection is expected; however, the resultant soft and hard tissue changes cannot be predicted nor controlled. Emergence profile is dimensionally limited and subject to continual deterioration.

FIGURE 9B—In the case of the Ankylos® system (DENTSPLY — Friadent, Mannheim, Germany); long term hard and soft tissue stability is expected, interdental papillary height gain can be demonstrated, no micro-movement occurs and as such, long lasting aesthetic outcomes are predictable as stable vertical and horizontal biologic width is the norm.

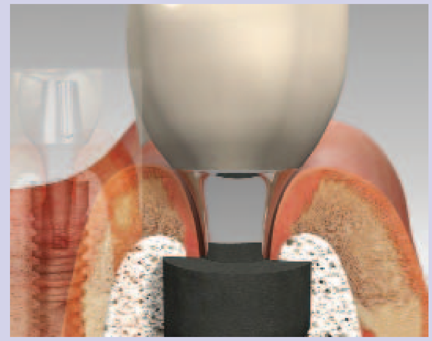


FIGURE 10—The tissue care connection created by the interface between a fixture and abutment should engender an ideal biologic width and provide; long-term hard tissue stability, long-term peri-implant soft tissue, a gain in interdental papilla height, no micromovement and long lasting aesthetic outcomes.

free sub-gingival connection is not possible. As indicated previously, the greatest strain is placed on the connecting screw. The screw is essentially the only device resisting strain in the connection apparatus, so it tends to loosen and/or fracture relatively easily. Once this cycle of failure is established, it recurs with increasing regularity.[39-41] Thus biologic width is endlessly subject to inflammatory instability due to micro-pumping from the interface gapping during function (Fig. 10)

In order to prevent screw loosening, various anti-rotation devices have been used which can engage into reciprocal slots on the inner surface of the implant. These slots can be difficult for a manufacturer to machine completely, and final forming in the corners is usually achieved by stamping. Sharp corners can act as stress concentrators, which under strain may cause micro-cracks that can eventually rupture the wall of the fixture body. Similarly, depending on the configuration of the anti-rotational components, an explosive force can develop during rotation. The design needs to minimize stress concentration and to resist the explosive forces generated during rotation. The necessary bulk and strength of the implant body wall can be difficult to obtain, particularly in small diameter implants. It is always preferable for fracture of a secondary component to occur before any rupture of the implant body takes place.

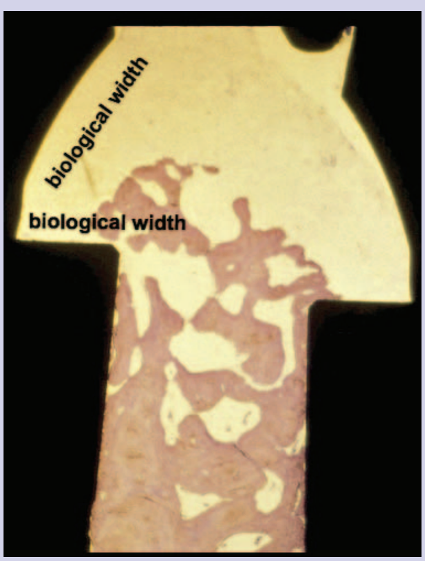
> Too great refinement is false delicacy, and true delicacy is solid refinement.
>
> — Francois Duc de la Rochefoucauld

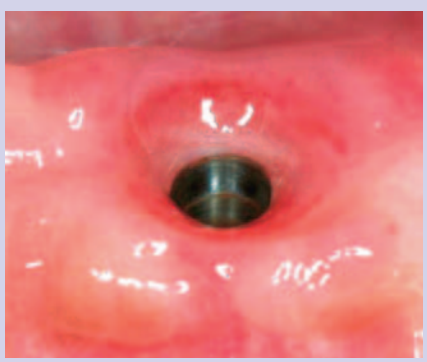
The stem of a Morse taper connector runs deep within the implant body, thus forming a stronger, more intimate attachment than a screw retained system. The internal walls of the fixture have a taper of less than 6° expressed as the ideal ratio of 5:17/1. As the stem is seated to place, the walls of the fixture channel cold weld the tapered connector. This secures the connection and reduces strain on the floating retaining screw which reduces the possibilities of screw fracture or loosening. As a result, it takes 30% more force to disengage the screw post than to engage it.[42] A precisely machined Morse taper prevents rotation of the abutment on the implant and eliminates the micro-gap present in many 2-stage implant systems. Accuracy of fit is further potentiated by the use of a transfer jig for placement and seating. This negates the potential for misfit inherent in single and double hex systems.

Repetitive micro-strains during function at the bone-implant interface can lead to implant loss.

In an attempt to improve survival by directing the stresses during function away from the dense cortical bone, the Ankylos implant was developed with a roughened, progressive thread system which reduces the stresses in areas of the cortical bone thus enabling an unconventional cancellous fixation concept as opposed to the traditional cortical fixation concept. The idea is to maximize stress transfer to the cancellous bone, hence minimizing saucerization and bone loss at the osseous crest. In addition, the precisely machined, tapered integrated screw connection (TIS) of the Ankylos fixture provides high resistance to bending and rotational torque during clinical function. The connecting elements feature a Morse taper, giving absolute friction lock anti-rotation to all abutments and a gap-free connection sub-gingivally. Abutment selection is independent of fixture diameter for all prosthetic steps. All abutments allow for screw-retained or cemented prostheses. Because the tapered abutment has a greater surface area for stress transfer to the implant than conventional abutment screws, there is no risk of abutment fracture or loosening (Figs. 11A-D).

The fundamentals and rudiments of dental procedures have remained relatively unchanged regardless of the explosive nature of the service mix. All dental procedures are comprehensive and inclusive; each successive procedure builds on the health status achieved by a prior effort. Periodontal prosthetic philosophies, concepts, principles and techniques buttressed by solid, sound foundations provide evidence based success. The inclusion of implant scaffolded prosthetics in the reconstruction of a natural dentition, rather than their use in replacing a natural dentition, will expand the therapeutic options available and further potentiate successful treatment outcomes. All this must come however, with an appreciation of inherent complexities and unexpected complications. The price to be paid for panaceas will always remain too dear for the patient and the clinician to bear. **OH**





FIGURES 11A-D—Abutments smaller than the diameter of the implant body (platform switching) in combination with an absence of micro-movement and micro-gap may protect the peri-implant soft and mineralized tissues, explaining the observed absence of bone resorption. As a result, immediate loading may not interfere with bone formation and did not have adverse effects on osseo-integration. As seen in images b, c and d, the use of a standardized major connector component (ANKYLOS PLUS™) as an integral design feature creates not only a cold weld fit, but the potential for bone regeneration above the height of the collars between proximate fixtures and the resultant tissue emergence profile is extraordinary.

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COMPLETE REFERENCES AVAILABLE UPON REQUEST.