The ideal restoration of endodontically treated teeth – structural and esthetic considerations: a review of the literature and clinical guidelines for the restorative clinician

Konrad Meyenberg, DMD
Private Office for Reconstructive Dentistry
Zürich, Switzerland

Correspondence to: Konrad Meyenberg
Private Office for Reconstructive Dentistry, Rennweg 58 / Eingang Oetenbachgasse 26, 8001 Zürich, Switzerland;
E-mail: k.meyenberg@bluewin.ch; Web: www.zahnaerzte-rennweg.ch
One of the most challenging dilemmas faced by today’s clinician is the management of the structurally and esthetically compromised endodontically treated tooth. Certainly, in recent years there has been a tendency to take the simplified approach of “extraction and implant” but this does not always prove to be as simple as we would like to think. Has the popularity of dental implantology made the restorative dentist complacent in regards to the possibilities that good endodontic, periodontal and restorative treatments can achieve? Without doubt the dental implant option has its place, and rightly so, but in many cases, I suspect, the endodontic/restorative option does not always receive its due merits.

Whenever we are faced with such a compromised tooth, we have to consider the following question: is the tooth maintainable? If so, then this is surely our primary goal. However, the question is complicated by the context – ie, is this a young patient? Is this a bridge abutment? Is there an esthetic challenge, ie, a dark tooth? In the younger patient, it may be desirable to maintain a potentially hopeless tooth for as long as possible in order to “buy time” and delay the day of implant placement and its subsequent eventual failure. Retreatment of a tooth is, more often than not, simpler with a broader range of options than retreatment of a failed implant, particularly in the esthetic zone. If this can be done for the younger patient, then why can’t it be done for the older patient? On the other hand, perhaps it is more predictable in a given case to remove the tooth and restore it with a dental implant restoration. These and other issues are real concerns we have as practitioners and it is important to have objective as well as the subjective criteria on which to base our decision for the choice of restorative protocol.

Are all endodontically treated teeth really less predictable than a dental implant-supported restoration? Are they really more likely to fail? Do they really have a poor prognosis? Do implants really have fewer complications? Is retreatment as easy? Do anterior and posterior teeth behave the same? When is the prognosis of the tooth unfavorable and at what point is extraction and an implant the best option? These and many other relevant questions are eloquently addressed below by our essayist and EAED Active Member, Dr Konrad Meyenberg. My hope is that this paper will serve to help us to question our treatment choices more critically in this area, suggest useful answers to many of the questions in this dilemma, provide us with objective criteria on which to base our judgements and finally offer solutions so that we can make better choices for the treatment of our patients.

Dr Tidu Mankoo, BDS
Abstract

In restorative dentistry, the non-vital tooth and its restoration have been extensively studied from both its structural and esthetic aspects. The restoration of endodontically treated teeth has much in common with modern implantology: both must include multifaceted biological, biomechanical and esthetic considerations with a profound understanding of materials and techniques; both are technique sensitive and both require a multidisciplinary approach. And for both, two fundamental principles from team sports apply well: firstly, the weakest link determines the limits, and secondly, it is a very long way to the top, but a very short way to failure.

Nevertheless, there is one major difference: if the tooth fails, there is the option of the implant, but if the implant fails, there is only another implant or nothing.

The aim of this essay is to try to answer some clinically relevant conceptual questions and to give some clinical guidelines regarding the reconstructive aspects, based on scientific evidence and clinical expertise.

Rebuilding the ideal tooth from an endodontically treated tooth – what does this mean?

Essentially, the goal is to restore the appearance and biomechanical properties comparable to those of a vital, completely intact tooth. In addition, the coronal restoration should prevent bacterial re-colonisation of the endodontically treated root canal system. Clinically, most of non-vital teeth must be considered as structurally and esthetically compromised. The fracture rate and as a consequence the risk for tooth loss is considerably higher compared to vital teeth.

Part 1: Structural considerations

What are the causes of fractures?

There are several causes for the increased risk of cracks in endodontically treated teeth to be considered. Cracks predispose the tooth immediately or after some time to fracture. The following four factors contribute to this predisposition (Figs 1–4):

- Structural loss of tooth substance due to pre-endodontic restorative procedures or the endodontically induces access cavity preparation and root canal enlargements.
- Increased brittleness by age induces changes in the dentin and the loss of free unbound water from the root canal lumen and the dentinal tubules in pulpless teeth.
- Weakening effects by endodontic irrigants (NaOCl, EDTA) and medications (CaOH₂) on dentin, effects of bacterial interactions with the dentin substrates, corrosive effects of restorative materials, and negative mechanical effects through crack inducing or crack propagating endodontic and restorative methods and instruments, including endodontic files.
- The reduced level of proprioception of non-vital teeth causes a reduced level of control of forces by the normal
protective neuromuscular inhibition mechanism.¹⁷

Some of these factors may be influenced or modified to improve the prognosis, however the most important factor for success is to avoid any unnecessary loss of tooth substance in general and to preserve as much as possible after removal of all decayed material.

Recent research shows that dentin has some very effective inherent properties to inhibit crack progression (fracture toughening mechanisms), to optimally distribute local stresses and to partially repair defects, as long as a tooth is vital.⁸,⁹ However, a non-vital tooth will lose some of these properties over time. A key consideration is that the amount of collagen fibers in endodontically treated...
teeth decreases, which means that this dentin is much less fatigue resistant. In addition, even vital dentin loses some of its initial strength over its lifetime: it shows a different fracture behavior as the mineral content increases over time and causes a less favorable fracture behavior because of the increased brittleness.

Restorative options: what is the ideal concept?

As a consequence, any attempts to restore a non-vital tooth must include not only the use of restorative materials with properties similar to the dental components, but also the use of clinical concepts that allow to compensate the inherent reduction of the mechanical resistance of endodontically treated teeth. A true so-called biomimetic concept therefore does not only implicate the use of particular materials similar in their properties to dentin and enamel, but also sometimes the use of particular materials with different properties to restore the incomplete tooth as a whole in all its mechanical, biological and esthetical aspects, above all if the remaining tooth structure is compromised.

Post or no post – are posts destructive?

In the past, fractures of teeth often have simply been attributed to inadequate restorative procedures, be it by the use of inadequate core materials or the use of posts and screws. The introduction of adhesive techniques and their successful integration in almost all current restorative procedures has allowed the clinician to dispense with posts in many indications, as they are no longer required for the retention of a core build-up.

However, mindful clinicians can still observe a relatively high rate of vertical root fractures despite the absence of posts and even with the use of adhesive techniques – above all in curved and small roots; indeed some authors report up to 20% of vertical fractures of endodontically treated teeth. Mandibular molars and maxillary premolars are most often affected. Provided there is enough coronal dentin structure (more than two-thirds available) it seems that there is no difference between teeth restored with or without posts in this respect. Interestingly in this article, 86% of molars with vertical root fractures had the fracture in a root without a post. Therefore, as long as no active posts or screws are used, which may produce detrimental lateral forces on the dentin walls, and as long as inadequate placement techniques with risk of perforations are not used, posts per se may not be considered as destructive.

When is a post indicated?

The main reason to use a post today is no longer to increase the retention and resistance of a core build-up, since there are very effective adhesive techniques available. As discussed, provided there is sufficient tooth structure available, there is no longer a need to place a post. In premolars with limited amount of tooth destruction and molars where, in general, more dentin walls with greater surface area can be engaged to be bonded as compared to anterior teeth, a direct bonded core build-up is
clinically the concept of choice; it can be regarded clinically as well established, reliable and perhaps preferable to conventional post-core concepts. In addition, by avoiding posts, the risk of cracks due to thin residual root walls or perforations can be eliminated.\textsuperscript{34}

For anterior teeth and heavily compromised premolars, however, this statement is limited to teeth that present with small to moderate defects and that will later not be crowned.\textsuperscript{35,36}

For posterior teeth, the best prognosis is achieved if – in addition to a bonded core foundation – a ferrule effect\textsuperscript{36} is created by the final restoration. This means that full cuspal coverage is used, be it a partial or full crown. Adhesive techniques alone without cuspal coverage may still lead to catastrophic failures over time (ie, untreated long axis fractures) and cannot be regarded as clinically safe.

It must be stated at this point that the ferrule effect is the most effective way of mechanical stabilization, ie, of optimizing the resistance form, of any endodontically treated teeth.\textsuperscript{38} Given the weaker structure, as previously discussed, the effect of the better load distribution into the cervical zone and the avoidance of any wedging effect by the post or core build-up into the coronal part of the root cannot be overemphasized. Therefore, in order to provide a ferrule in situations without sufficient tooth structure above the zone of the biological width, orthodontic extrusion or surgical crown lengthening should be considered. A ferrule length of 1.5 to 2 mm is recommended.\textsuperscript{39}

It must also be stated that, obviously, the lack of coronal tooth structure cannot be compensated simply by adhesive techniques using fiber posts and composite cores. In a recent long-term study over 7 to 11 years, the mechanical failures reached 7 to 11\% and were always related to a lack of coronal tooth structure.\textsuperscript{40}

If anterior teeth and premolars present with large defects that require crowning, however, adequate transfer of forces from the crown into the core build-up and from there into the root is not possible without a post. Importantly, the function of the post is not only the increase of the retention of the core, but also the optimization of the resistance form. In addition, the mechanical properties of a composite core alone may also not be sufficient in the case of a narrow abutment diameter and cannot reduce high stresses in the critical cervical area, which in such a case, is prone to horizontal fractures.\textsuperscript{41} A clinical study over 3 to 6 years with crowns bonded directly to a reduced macroretention geometry without posts\textsuperscript{42} clearly showed that the concept can work for molars (87–95\% success, depending from the amount of residual cavity walls), but did not work for premolars, if there were no cavity walls at all and the crown was just bonded directly into the residual pulp chamber (67\% success rate).

Therefore, the purpose of a post and core as a unit is primarily to transfer the loads into the root and secondly, the post is used as a reinforcing element of the core build-up.

The downside of this concept is the weakening effect on the root itself;\textsuperscript{41,43} to compensate for this, the ferrule effect must be incorporated into the restoration design.
The ferrule effect may also compensate unexpected breakdown of adhesion after bonding and luting procedures in unqualified dentin conditions. A safe clinical concept always implies the incorporation of a ‘belt and braces’ approach to offset routes of potential failure.\(^{42-45}\)

A special indication for a post is the immature root, presenting with a large root canal.

Obviously neither gutta-percha nor MTA nor composite have a significant reinforcing effect. In this instance, the only significant reinforcing effect is achieved with a post.\(^{46}\) This is in line with the clinical observation of increased risk of fracture in immature teeth left without post and core-build up after endodontic treatment.

**If a post is indicated:**

**what post concept should be used: stiff or flexible?**

“If something can break, it will break, and it will always break at the weakest point” – this basic finding and classic rule for construction is also true for this application and may explain the significant controversies regarding what would be the best of all the available concepts. The question may be not whether something will break, but rather where it will break.

Almost all dental materials have been used clinically for posts. Still clinically relevant today are gold-alloys, chrome-cobalt, titanium, zirconia and glass fiber posts. Carbon fiber posts have no clinical significance due to poor clinical performance and disastrous potential; therefore they will not be discussed in this article.

Basically there are two conflicting issues causing some disagreements on the ideal material of a post.\(^2\) From a mechanical standpoint, it is evident that a post stiffer than dentin can take up more load but induces more stress in some apical parts of the root, which can increase the risk of a vertical root fracture. Conversely, a post that has an elastic modulus closer to dentin will, in fact, induce less stress concentration apically in the root, but more in the cervical region.

In addition, the interface between post and core and between core and dentin is also subjected to stress, so one can expect to see more root fractures (irreparable fractures) with stiffer posts made from metallic or ceramic materials, whereas more flexible posts would show more post fractures, debonding of core materials and loss of retention (possibly repairable) with subsequent problems of leakage and caries. The latter may lead to endodontic reinfection and catastrophic coronal destruction of tooth substance, thus leveling out the potential advantage of this latter concept over the first one.

The dilemma for the clinician is the meaningful interpretation of the literature, as countless studies have been published in this field, most of them being \textit{in vitro} studies with questionable clinical potential relevance. Numerous theoretical studies using finite element analysis have also been performed, which would all need to be verified according to classic engineering principles in a real model, but only a minority of the \textit{in vitro} studies have been performed with dynamic or fatigue loading under a simulated oral environment. Another difficulty is that study results are also influenced by
the structural condition, various types of natural teeth utilized and the respective loading pattern.

One of the more clinically relevant *in vitro* studies compared cast posts and cores, titanium (Ti) posts with composite cores, zirconia posts with composite cores and zirconia posts with ceramic cores, using, in all groups, adhesive techniques and a ferrule of 1 to 2 mm on central incisors where all teeth were crowned. The most favorable results in terms of fracture strength (521 N) and survival rate (100%) could be achieved with the stiffest concept (zirconia posts with a ceramic core), and the least favorable with the cast post and core system (408 N, 87.5%).

In contrast to this study with ideal tooth substrate, another study compared different degrees of tooth destruction, using fiber posts and composite cores or composite cores alone on premolars. It was shown that posts had a significant positive effect on fracture strength if only 1 or 2 cavity walls were left, whereas no difference could be found if 3 or 4 cavity walls were left. However, if a completely flat profile without any substance above the preparation line is used, most likely the post will debond as predominant mode of failure.

Two facts are of special importance in the judgment of studies comparing different concepts:

- The results of these *in vitro* studies largely depend on the presence or absence of a final restoration (crown). Principally, differences in materials of posts and cores level out from the moment where a crown is placed.
- If metal-free post and core concepts are to be successfully used, the establishment of proper bonding between all substrates is of paramount importance. If bonding fails, much less favorable stress patterns occur both in the root, above all in the critical cervical area, and in the post and core itself. As a clinical consequence, loss of retention of the core and post is still unfortunately the major complication.

Most of the clinical studies are difficult to interpret in their outcome, since the amount of tooth loss and the condition of the remaining dentin (pre-existing cracks, aging, endodontic treatment modalities) are not known and may have influenced the choice of the concept.

The scientific dilemma is very nicely expressed in a systematic review about the simple final question, whether a crown or a filling is more effective in the clinical performance for an endodontically treated tooth. The authors conclude “There is insufficient evidence to support or refute the effectiveness of conventional fillings over crowns for the restoration of root filled teeth. Until more evidence becomes available clinicians should continue to base decisions on how to restore root filled teeth on their own clinical experience, whilst taking into consideration the individual circumstances and preferences of their patients.”

This statement shows not only the complexity of the topic, but also that clinical multifactorial reality does not allow clear definition of one simple generally valid concept.

Nevertheless, there is still a need for clear clinical guidelines, based on scientific evidence paired with clinical
expertise. Only this combination finally leads to clinical evidence.

As a conclusion from numerous clinical studies, it must be stated that there is no superior concept in all respects. Both direct and indirect concepts and gold, Ti, fiber and zirconia posts work well if the respective concepts are properly executed. The single most important point is to preserve as much remaining tooth structure as possible.41,49,54-57

Two additional arguments may require consideration for the reconstructive clinician: a) fiber posts offer the highest potential for reintervention due to their relative ease of removal, however their successful use clinically is much more technique sensitive,58 and b) post and cores with a high modulus of elasticity (metal or zirconia) offer a higher fracture resistance as a foundation of the crown,50 which may be of significance for the long-term success of all-ceramic crowns.59,60

What about bonding a post into the root canal space? Does bonding help in cases with extended amount of tooth destruction? What is the ideal surface conditioning of fiber posts?

Looking at the results of a recent clinical 10-year fiber post study, a surprisingly high annual failure rate of 4.6% is reported and an overall failure rate of 37%, with 11% fiber post fractures and 11% post debondings.61 The highest probability of a failure was reported for anterior teeth with no cavity walls.

This is confirmed by another clinical study62 where premolars of varying degrees of destruction were restored with different concepts of build-ups. All teeth were finally crowned with porcelain fused to metal (PFM) crowns. An overall failure rate in this 6-year survival study of 40% was reported. When only a circular ferrule of 2 mm or less was left, the failure rate increased to nearly 90 to 100% for the no post concept, to 40 to 60% for prefabricated posts, and to around 70% for the customized post concept.

The results clearly suggest that prefabricated fiber posts are superior to customized fiber posts (glassfiber band, resin impregnated) or composite cores without any posts, if there are only 2 walls or less remaining. However, even if in addition to the bonded core a prefabricated fiber post is used, the concept obviously fails to be convincingly successful in cases with extended tooth destruction.

In contrast to this 40% overall failure rate over 6 years of non-metallic posts and build-ups, a 10-year report of prefabricated metal posts and cast metal posts and cores resulted in a 15.4% and 17.4% overall failure rate.63

Retention

The almost doubled overall failure rate of fiber posts and the surprisingly high debonding rate must raise the question about the effectiveness and efficiency of this concept in general practice. Perhaps it is unsurprising given the inherently more technique-sensitive concept of the required adhesive techniques and the lack of a simple clear user protocol.

A recent study compared the retention of different fiber posts with different surface conditionings (performed according to the manufacturer’s recommendations) and luting agents in den-
Ti-posts luted with conventional zinc phosphate-cement served as the control group. The control Ti-post showed, together with some combinations of the test group, the highest pull-out strength, whereas some combinations of the test group showed surprisingly low values. This is in line with another study, where adhesively luted fiber posts were not superior to gold posts either adhesively luted or conventionally cemented with glass ionomer cement.

**Adhesion to radicular dentin**
Adhesively luting a post into root dentin is a controversial issue. Conflicting results have been published about the efficacy of bonding to radicular dentin. Probably due to the structural differences in radicular dentin, bond strengths improve from the apical to the coronal section. Comparing the use of complicated separated dentin bonding and luting procedures with simpler self-etching cements, it seems clinically more reliable to use self-etching and self priming cements taking into account the potentially somewhat lower bond strength to dentin. Inadequate ability to cure the luting agents precludes the use of light-curing materials. Dual-cure or chemically curing materials should be used instead, since different fiber posts indeed differ in their light transmitting properties, however posts with optimal mechanical properties do not allow enough light penetrating all over the whole length of the post to sufficiently polymerize light-cured materials.

**Adhesion to post surface**
To improve bond strength to the prefabricated fiber posts, chemical (silane, etching with hydrogen peroxide for 20 min, or methylene chloride for 5 s) or micromechanical treatments (sandblasting) or a combination of both have been proposed. Surprisingly, sandblasting seems to not affect the mechanical properties of the fiber posts. Sandblasting with silanization is, therefore, an efficient, simple and predictable way of surface conditioning a fiber post before bonding. However, fiber posts are susceptible to water degradation, and damaging the surface will increase this phenomenon. Thus, a predictable bonding procedure that completely seals the post surface and avoids any voids is of paramount importance to preserve fracture resistance. Some manufacturers now use a coating on their posts to further simplify and improve the bonding. Nevertheless, care should be taken to consider both the manufacturers’ recommendations and their scientific basis.

**Mechanical properties**
Major differences in the mechanical properties of different brands of posts is another critical point. Since there are now countless brands of posts on the market with a sometimes-unknown origin, a proper selection based on independent scientific investigations is imperative to avoid basic mechanical failures. Using a fatigue resistance test, a difference of roughly 7,000 cycles until fracture for the worst and up to 2,000,000 cycles for the best post in this respect (equivalent to no breakage) could be shown. The quality of the manufacturing processes including type of fiber and matrix, pre-tensioning of fibers, bond between fibers and matrix, among other factors, play an important role.
Therefore, both a sensitive indication and technique is mandatory for the successful use of the concept of fiber posts combined with composite cores (Figs 5 to 11).
Concluding remarks regarding the structural aspects

The following statements regarding the structural aspects may be made:

- Where a crown is fabricated and a proper ferrule effect is created, neither the material (Ti, gold alloys, zirconia, glass fiber) nor the shape and length of the post are a significant influence, as long as clinically reasonable concepts are used.

- Conversely, insufficient coronal tooth structure will always lead to an increased failure rate independent of the concept of restoration.

- Increasing the coronal diameter of the post helps to reduce the fracture risk of all posts, however the residual dentin wall thickness needs to be considered.

- Huge differences in the quality of fiber posts require a careful selection to avoid post fractures.

- Materials with potential of corrosion (stainless steel, brass) may induce fractures of materials and dentin and therefore should not be used.

- Adhesive cementation of fiber posts is mandatory.

- Adhesive cementation of metallic posts is not mandatory.

- Core build-ups should always be bonded, even if a metal post is not bonded.

Regarding the clinical reality, the following additional statements must be made:

- Ceramic posts (zirconia) cannot be removed after luting, offer no potential for reintervention and should therefore be used in selected cases only.

- For abutment teeth presenting large defects and requiring crowning, or longer span bridges, or in general heavy loads, metallic posts are preferable over fiber posts (Figs 12 to 14).
References, Part 1


30. Souza EM, do Nascimento LM, Maia Filho EM, Alves CM. The impact of post preparation on the residual dentin thickness of maxil-
31. Krejci I, Duc O, Dietschi D, de Campos. Marginal adapta-
tion, retention and fracture resistance of adhesive com-
34. Souza EM, do Nascimento LM, Maia Filho EM, Alves CM. The impact of post preparation on the residual dentin thickness of maxil-
35. Heydecke G, Butz F, Strub JR. Fracture strength and survival rate of endodont-
36. Ferrari M, Cagidiaco MC, Grandini S, De Sanctis M, Goracci C. Post placement affects survival of endodont-
40. Ferrari M, Cagidiaco MC, Goracci C, Vichi A, Mason PN, Radovic I, Tay F. Long-
41. Pierrisnard L, Bohin F, Renault P, Barquins M. Coro-
no-radicular reconstruction of pulpless teeth: a mechanici-
al study using finite ele-
42. Bindl A, Richter B, Môrmann WH. Survival of ceramic computer-aided design/ 
43. Sathorn C, Palamara JE, Palamara D, Messer HH. Effect of root canal size and 
external root surface mor-
phology on fracture suscep-
45. Heydecke G, Butz F, Hus-
sein A, Strub JR. Fracture strength after dynamic load-
ing of endodontically treated teeth restored with different post-and-core systems. J Prostheth Dent 2002;87:438–
445.
46. Schmoldt SJ, Kirkpatrick TC, Rutledge RE, Yaccino JM. Reinforcement of simulated immature roots restored with composite resin, mineral trioxide aggregate, gutta-
47. Mangold JT, Kern M. Influ-
ence of glass-fiber posts on the fracture resistance and failure pattern of endodonti-
49. Heydecke G, Peters MC. The restoration of endodonti-
cally treated, single-rooted teeth with cast or direct posts and cores: a system-
50. Dietschi D, Duc O, Krejci I, Sadan A. Biomechani-
51. Krejci I, Duc O, Dietschi D, de Campos E. Marginal adaptation, retention and fracture resistance of adhe-
53. Rasimic BJ, Wan J, Musi-
kant BL, Deutsch AS. A review of failure modes in teeth restored with adhe-
55. Fokkinga WA, Kreulen CM, Bronkhorst EM, Creugers NH. Up to 17-year controlled
77. Valandro LF, Yoshiga S, de Melo RM, Galliano GA, Mallmann A, Marinho CP, Bottino MA. Microtensile bond strength between a quartz fiber post and a resin cement: effect of post sur-
Part 2: Esthetic considerations

Introduction

In addition to the numerous issues discussed in part 1 of this paper, non-vital teeth are frequently esthetically compromised. This frequently presents significant and special challenges when it comes to meeting the demand for natural-looking, esthetically pleasing teeth sought by our patients today.

The aim of the second part of this paper is to try to answer several clinically relevant conceptual questions and to provide some clinical guidelines regarding the management of the esthetic aspects, based on scientific evidence and clinical expertise.

Why are most endodontically treated teeth dark?

The discoloration of endodontically treated teeth is a common observation. In the posterior region, this phenomenon is seldom esthetically disturbing or is largely addressed with full crowns, since endodontically treated posterior teeth present mostly with large reconstructions that require optimal stabilization by full or partial crowns.

In the anterior zone, however, esthetics can be strongly disturbed by 3 negative effects:

- Discolouration of the clinical crown.
- Discolouration of the cervical region.
- Discolouration of the gingiva and mucosa.

There are various causes of these endodontically induced intrinsic discolorations:1-3

- Intrapulpal haemorrhage.
- Pulpal necrosis.
- Incomplete removal of pulp tissue during the endodontic treatment.
- Endodontic irrigants, medications and root canal filling material (root and cervical zone).
- Restorative materials (cervical zone and crown).
- Coronal leakage.
- Dentin sclerosis.

References

Unfortunately almost all root canal sealers including Zinc Oxide-Eugenol and AH 26 (to a lesser extent) lead to discoloration, above all in the cervical zone. Also the use of MTA, be it grey or white, will ultimately lead to a greyish appearance or darkening of the root. Furthermore, the calcification process in the dentin through obliteration of the dentinal tubules and changes in the free water content before and after endodontic treatment and through aging processes, contributes to an altered optical appearance in addition to the increased brittleness.

How can we improve the color of the tooth substance? Bleaching or replacing discoloured coronal dentin?

Although some of the above mentioned negative factors can be clinically modified, it is evident that a non-vital tooth inevitably loses some esthetic qualities in terms of the color. As a matter of principle, replacing discolored dentin to correct the color is not the preferable option from a structural viewpoint. In part 1, the mechanical aspects to support this axiom have already been extensively discussed.

Therefore, bleaching the existing substance is always the better option, if we agree on the principle that “having a discolored tooth is preferable to having no tooth”. Most discolorations are bleachable except those caused by metal ions (amalgam, or silver and other heavy metal containing materials). So the only indication to remove discolored dentin may be if small spots that do not contribute to the structural resistance of the tooth are heavily discolored and do not respond to the bleaching procedure.

Do bleaching procedures lead to external resorption?

Cervical root resorption is a serious complication that is difficult to treat and ultimately can lead to tooth loss. There are various reasons for this phenomenon. Orthodontic treatment and tooth trauma are the most common predisposing factor. Internal bleaching may increase the combinatorial risk, however it seems to be limited to cases where extensive concentrations of H$_2$O$_2$ combined with heat (the thermo-catalytic method) was used. The presence of defects at the cemento-enamel junction seem to play a major role, allowing the bleaching agent to penetrate into the periodontal space.

The recommendations today are therefore not to heat the bleaching agent in the access cavity, to seal the residual root filling well before application of the bleaching agent and to generally use less aggressive bleaching chemicals instead of high concentrations of H$_2$O$_2$.

The best clinical compromise of effect, side-effects, risks and long-term experience is in the use of the so called “walking bleach technique” where, classically, sodium perborate is mixed with water.

In the author’s long-term experience, this is clinically as efficient as other more aggressive chemicals, provided a correct cervical and coronal seal of the bleaching cavity have been realized. The cervical seal is preferably achieved with a modified glass ionomer cement, classically applied at the level of the con-
nective tissue attachment, whereas the coronal seal is achieved with adhesively luted composite to ensure an optimal penetration of the bleaching agent into the dentin. Hence, leaving the access cavity open and using at-home techniques with open trays is not advisable.\textsuperscript{17}

Success largely depends from the application duration of the bleaching agent (2–3 days, 2–3 times) and by far outperforms alternative quick in-office techniques in the long run.\textsuperscript{18} In a recent study it could also be shown that this concept compares very favorably to more aggressive mixtures of chemicals in terms of $\text{H}_2\text{O}_2$ leakage at different root locations with and without external defects.\textsuperscript{19,20}

Since cervical defects are difficult to detect with conventional radiographs and require cone beam computed tomography (CBCT) techniques,\textsuperscript{21} the use of this less-aggressive concept makes additional sense in avoiding added unknown risks while producing good aesthetic results.

Do bleaching procedures weaken the tooth – or may dark roots also be bleached?

Recent research clearly shows that bleaching chemicals weaken tooth substance.

Since the endodontic treatment itself already weakens the dentin considerably through chemical and mechanical effects\textsuperscript{22-24} by 30 to 60% in strength,\textsuperscript{25} additional care must be taken if a bleaching procedure is being considered.

First of all, internal removal of discolored dentin should be avoided. It does not lead to better results with the described bleaching technique and will further compromise the strength of the residual tooth structure. This is an important consideration particularly if additional reconstructive measures are to be executed\textsuperscript{26} and if the potential for re-intervention is taken into account.

Second, as mentioned, bleaching agents themselves lead to a weakening of the tooth structure through the chemical modification of the dentin.\textsuperscript{27,28} A recent publication supported the use of sodium perborate mixed with water in this respect, since this combination led to a significantly smaller additional opening of the dentinal tubules compared to all other bleaching agents. Interestingly 45% carbamide peroxide caused the worst effect.\textsuperscript{29}

Another important consideration is the influence of bleaching on dentin bonding. As emphasized in part 1, the quality of the internal reconstruction after endodontic therapy is of key importance in reconstituting the resistance to fracture. Using an adhesive approach is advisable but technique sensitive and, in general, all bleaching agents lead to reduced bond strengths and increased microleakage.\textsuperscript{30} Consequently, the use of antioxidants has been advocated to counteract this effect (eg, sodium ascorbate) and/or delaying the bonding procedure for at least 10 days after washing out the bleaching agent\textsuperscript{31} The antioxidant is especially necessary and should be mandatory if bonding with simplified single bond dentin adhesives,\textsuperscript{32} or if delayed bonding is not warranted or possible.\textsuperscript{33}

However, good dentin adhesion can be achieved if: a) sodium perborate mixed with water is used to bleach, b) the tooth is left with saline solution for 7 days after
removal of the bleaching agent, and c) a scientifically and clinically well established self-etching 2-step dentin bonding system (eg Clearfil SE bond) is utilized.\textsuperscript{34} For enamel, the same principle of waiting after washing off the bleaching agent is a simple and successful strategy. Recent proposals for new resin formulations that are supposed to allow immediate bonding after bleaching have not proved as effective.\textsuperscript{35}

Since adhesion within the root remains a challenge even in ideal experimental conditions – owing to unfavorable ovoid root canal configurations and dentin microstructure in the deeper parts of the root canal\textsuperscript{36} – the root should not be further compromised by using bleaching techniques inside the root canal. As long as the intracoronal bleaching is performed within the access cavity reaching to the level where the connective tissue attachment ends coronally, the results constitute a sufficient compromise esthetically,\textsuperscript{26} even in the critical cervical zone (Figs 15–23).

**Fig 15** Case 3: discolored non-vital right central incisor with PFM crown, initial clinical situation.

**Fig 16** Case 3: initial radiographic situation. A carbon composite post had been placed.

**Fig 17** Case 3: abutment tooth after crown and post removal.

**Fig 18** Case 3: hollow composite build-up for internal bleaching of coronal part of the abutment tooth.
Fig 19  Case 3: completed build-up of abutment tooth with bonded fiber post and core, after internal bleaching with sodium perborate and water.

Fig 20  Case 3: glass ceramic crown, layering technique.

Fig 21  Case 3: final clinical result.

Fig 22  Case 3: final radiograph, showing good adaptation of the short fiber post and bonded core to the dentinal walls (light cured materials used).
What about the predictability and stability of bleaching procedures?

There has been some debate about the predictability and long-term effectiveness of internal bleaching, with described esthetic success rates of around 90% after 2 years, 75% after 5 years and 60% after 16 years. The potential causes for the recurrence of discoloration have been suggested as: a) the same substances as those having caused the initial discoloration, or b) penetration of pigments from the oral cavity, or c) bacterial reinfection of the root canal system with subsequent infiltration into the cervical and coronal dentin. From long-term studies and clinical observations, the following can be concluded:

- Internal bleaching is a technique-sensitive approach. Potential reasons for failures are numerous, with coronal or apical leakage being the most frequent, and “short-cut” treatment protocols are more likely to have problems. Both the coronal and the apical-cervical seal, along with the optical quality of the access restoration, account for success or failure.
- The prognosis of the bleaching procedure is more prone to recurrence of discoloration if the tooth became rapidly discolored after the endodontic treatment.
- Subjective and objective satisfaction of the dentist or the patient may differ substantially.
- The potential for intervention and the concept of a progressive (conservative) approach during the lifetime of a discolored tooth are essential. Aggressive reconstructive concepts based just on esthetic considerations and early crowning can lead to premature tooth loss. Therefore, bleaching instead of removing tooth substance is the preferable treatment, both for non-reconstructive and reconstructive cases.

May crowns or veneers compensate darkened coronal tooth structure?

First of all it is important to understand the concept of illumination of the oral tissues. The tooth with its clinical crown and root, the gingiva, the bone and the periodontium form an optical unit. Light is transmitted by diffuse reflection into the tissues. It is therefore critical not to disturb this delicate system with discol-
orations or by the introduction of inadequate opaque or dark restorative materials. Of particular importance in this respect is a soft color transition from the cervical third of the clinical crown into the adjacent gingival tissues.

Since the mid 1960s, dental technicians and prosthodontists tried to implement this concept in order to improve the esthetics of full crown margins. In the 1980s, PFM crowns without metal collars were introduced, using shoulder and veneering porcelains with better light conducting properties to illuminate the adjacent tissues.45-47 Despite these efforts, the results were never completely satisfying when the underlying tooth structure was dark, or if there were vital and rather translucent teeth to be matched. Hence the search and development of true light conducting materials as frameworks with lower opacity than metal or the pre-existing all-ceramic cores.48

Today, in the case of vital teeth with adequate tooth substance, more conservative bonded porcelain restorations, such as veneers and anterior partial all-ceramic crowns, are increasingly the treatment of choice as compared to full crowns, due to esthetic, technical and biological advantages.49-51 It is important to understand that the success of these restorations is largely based on the esthetic and mechanical advantages of the natural uncompromised tooth substrate as the foundation of the restoration rather than an artificial substrate. As a consequence of this success, the concept has been extended to endodontically treated teeth, with the idea behind to convert darkened tooth structure into vital looking tissues.26,52,53 Naturally this is not only relevant to bonded laminates and all-ceramic partial crowns, as a wide variety of all-ceramic crown systems exist today with excellent optical properties and long-term survival, in particular, the new generation of glass-ceramic materials.54-56 In addition, these materials allow the provision of bonded full coverage “veneer type” crowns with reduced preparation similar to 360-degree veneer preparation (Figs 5–11).

Consequently, the management of discolored tooth substrate becomes increasingly important. It should be remembered that all attempts to ‘mask out’ discolored tooth substance will invariably end up with increased opacity and therefore unnatural reflection of the light instead of a diffuse reflection inside the materials. This is of particular importance when veneering a tooth with a discolored cervical zone, as the fine veneer margins cannot create the appropriate color transition from the tooth crown into the gingiva. If a full crown is provided in such a case, a pleasing result can be achieved by using opaque all-ceramic framework materials, provided that adjacent structures are also more opaque and the gingival tissue is thick, but this is rather the exception than the rule.57,58 The same is true if opaque cements are used to cover dark underlying substance.

Above all, trying to mask out discolored teeth should not result in over-preparation:59 the mission statement of Hippocrates primum nihil nocere (first do no harm) should also be the guiding principle here (Figs 24 and 25).

Thus the clinical concept for management of discolored tooth substance should always consider internal bleaching as first option, even if the result will not be absolutely perfect.
If the tooth needs an additional indirect restoration, a veneer or full coverage veneer-crown is an attractive and less invasive solution. In the author’s own experience over the last 15 years from when the concept first was used, long-term results for esthetics and survival rates in both types of restorations are comparable to all-ceramic crowns. However, in the literature there are only studies with vital teeth available at the moment, which show a survival rate of 93.5% over 20 years for veneers and 100% for extended veneers over 5 years.60,61 The observation of small superficial cracks not influencing survival is similar to what can be observed within the enamel of natural teeth.

One drawback certainly is if the discolored tooth has already been restored with a post. If removal of the post without risk of damage to the root is viable, then the internal bleaching can be performed before a new post and core is fabricated. If this is considered too risky, metallic posts and cores can at least be masked with a tooth-colored opaquer and composite to avoid to improve the substrate color for an all-ceramic framework.

This leads to the next question: Can tooth-colored posts enhance the color of dark roots?

Tooth-colored posts have long been advocated in esthetic dentistry. Since early trials around 1965 by John McLean with Alumina posts, the concept has been further developed to mechanically more reliable posts, with the introduction of the first Zirconia posts in 199562,63 and the first fiber posts in 1990.64

The proposed reasons for tooth-colored posts for esthetics in root treated teeth are:

- To illuminate the root and cervical region and thus brighten up darkened tooth substance.
To prevent any darkening effect of a post on non-discolored tooth substance.

To create a tooth-colored basis for the core and the crown.

While the first reason has already been disputed early on by experienced clinicians not being able to see any difference in the color between a metallic post and a tooth-colored post put into the same dark root under natural light conditions, the second two points are good arguments for tooth-colored posts. In fact a recent study showed that there is no difference in the cervical color of abutment teeth between white and metallic posts, however tooth-colored posts and cores were beneficial for the overall color of the all-ceramic crowns. This is in line with observations of clinicians aware of these subtle differences.

Some care must be taken when trying to translate in vitro studies about color influences into clinical practice. Some subtle components of the color, such as the quality of the internal diffuse reflection depending on the intensity of light and the softness of the transition into the marginal gingiva cannot be measured by photospectroscopic studies and may lead to incorrect clinical recommendations in specific cases.

However, given the clinical and scientific evidence, there is actually little reason to take out existing well adapted and luted cast post and cores if the remaining dentin itself is not discolored and does not require bleaching. It is clinically sufficient to mask the buccal part of the metal with a tooth-colored opaquer. If space and residual thickness of a gold alloy post and core do not allow to do this, another smart approach is to polish the buccal part of the exposed metal to a high gloss, thus creating total reflection of the light at the core surface. This concept has been widely used by the author for years with no adverse effects regarding the retention of the luted crowns (Figs 26–30).

In conclusion, it can be stated that the color of the remaining tooth substrate is of much greater importance than the color of the post and cannot be influenced positively by the post in the cervical and apical region, however having a tooth-colored post is beneficial for the core.

Fig 27  Case 5: final picture showing the good reflection properties of the polished metal part of the left central abutment tooth.

Fig 28  Case 6: abutment teeth with various degrees of discolorations.
Can soft tissue thickening compensate darkened cervical root structure?

A soft color transition from the crown into the soft tissue is essential for an esthetically pleasing result. In the preceding pages, the focus was placed on the root and crown of the tooth and how negative effects can be managed. However, if discolorations are still present in the critical cervical supra- and subgingival zone, it makes sense to consider influencing the soft tissue characteristics.

The margin of the soft tissue covering the cervical part of the root plays an important role as a “curtain” to hide unpleasing structures. In addition, the buccal bone plate has also some masking effect over a discolored root. A thick bone plate can virtually completely mask out the root discoloration. In periodontology, there is little information available about the masking effect of the soft tissue. In oral implantology, however, some studies have been performed looking at the influence of various abutment materials on the color of the existing soft tissues, and how variations in the soft tissue thickness can modify the overall color resulting from abutment and covering soft tissue. Since these abutments all have a subgingival component and a titanium implant base, this would appear to offer a situation well in line with a discolored root. Comparing zirconia, polished gold alloys and machined titanium in a pig model, a visible difference was always present if the tissue thickness was below 2 mm. Between 2 to 3 mm in thickness, only zirconia (regardless of any veneering) did not induce a change. If the thickness was 3 mm or more, the material itself had no influence. In a human study, comparing metal abutments and PFM crowns with all-ceramic abutments and crowns, the latter behaved better, but there was still a visible difference for both groups compared to the adjacent teeth. Another study presented similar results, although no correlation between the thickness of the mucosa and the respective amount of discoloration could be found.

In essence, the fiber content and the degree of keratinization may play a more important role for the masking ability than the soft tissue thickness alone. In this respect, the use of a connective tissue graft taken from the palate with its higher content of collagen fibers is the most promising approach using an envelope technique to improve the esthetic integration of the augmented tissue. Some modifications in the technique, including a microsurgical approach, have been introduced to further decrease
healing complications and unesthetic tissue scars.\textsuperscript{74,75}

An additional benefit of this approach is the easier tissue handling during the reconstructive phase and the prevention of post-reconstructive recessions over time, which may expose further discolored root parts. Indeed, since many of the discolored teeth exhibit some cervical tissue loss over time anyway, this procedure can also be considered as a preventive treatment of a cervical recession,\textsuperscript{76} dealing not primarily with health, but with stable, esthetic tissue levels. It may also serve to counteract the loss in cervical tissue height that occurs by tissue modeling during the aging process, which is more noticed around discolored roots and is independent of the presence or absence of dental restorations.

As a conclusion, soft tissue thickening may not completely solve the problem of the discolored cervical hard and soft tissue zone, but it can improve the overall result by at least stabilizing soft tissue contours and preventing further exposure of discolored root surfaces.

Final consideration: at what point should we give up and extract?

It is fair to state that a tooth should be saved as long as there is a predictable way to functionally and biologically do so with a reasonable prognosis. This 2-part article has shown various possibilities to overcome classic biomechanical and esthetic problems with respect to minimizing reconstructive risks. The basis for reconstructive survival in the context of this article, however, is the quality of the endodontic treatment as the starting point.

It can also be stated that today too many teeth are extracted in favor of implants, with insufficient regard for the extensive reconstructive options available to maintain them. Furthermore, the
short- and long-term biologic, esthetic and technical complications of implants are not fully appreciated. Unfortunately, poor endodontic treatment is still a major factor in premature tooth loss. However, if performed correctly, results are at least as good as replacement with implants for single units. It is striking that despite this fact, today a tendency towards a more extraction-oriented reconstructive concept can be observed in practice. There are two main reasons for this.

The first reason is that in clinical decision-making, the predictability of the whole procedure is of primary importance in respect of complications and cost. Obviously there is some pessimism among clinicians regarding the prognosis of endodontic treatments in general and this is not completely unfounded. The combined failure rate of endodontically treated teeth in general practice is higher than described in earlier reports: over 4 years a cumulative failure rate of up to 20% is documented. In general, the outcome of endodontic treatments may have been overestimated in previously published reviews because of the general lack of correct apical diagnosis. If high-resolution CBCT is not used, often the endodontic status cannot correctly be analyzed. The authors of a current review state: “In conclusion, the serious limitations of longitudinal clinical studies restrict the correct interpretation of root canal treatment outcomes. Systematic reviews reporting the success rates of root canal treatment without referring to these limitations may mislead readers”. Therefore, the trend towards simplified endodontic protocols may also be based on incorrect interpretations of previous studies and may produce less successful results than expected or than achieved with the classic concepts of experienced endodontic specialists. A long-term study over 30 years, conducted in a private practice by a specialist, documented an overall success rate of 91.5%. Initial endodontic treatments had a higher success rate (94%) compared to the non-surgical retreatment group (86%). This shows very clearly how important the quality of the first endodontic treatment is for the long-term success. In addition, the coronal restoration has a significant influence in the success of the endodontic treatment. Thus, to strive in every respect for an optimal restoration is as essential as an optimal endodontic treatment alone.

The second reason is that measures to potentially save a compromised tooth can later preclude the placement of an implant or make it very demanding. Therefore, if an endodontic retreatment due to recurrent apical pathology is considered, above all, careful diagnostic steps including soft and hard tissue probing and radiographs are required. Conventional radiographs do not allow proper analysis and interpretation of the root and remaining bone housing around the root. The possible causes for the endodontic failure (eg, crack, fracture, perforation, insufficient root filling or accessory root canals) cannot be properly established without a high-resolution CBCT and consequently, the prognosis and appropriate treatment approach can only be determined based on an accurate diagnosis.

Periapical microsurgery should be performed exclusively if non-surgical endodontic retreatment is not viable,
and if the remaining bone housing is sufficient. The surgical approach seems to be more successful in the short term, but less so in the long term: 83% over 4 to 6 years for the non-surgical approach, versus 63% over more than 6 years for the surgical approach. In addition, the added bone loss caused by the surgical access osteotomy and incomplete healing can make the placement of an implant after a potential failure and eventful extraction very difficult.

Ultimately, when we examine the treatment outcome of implant versus non-vital tooth-supported restorations, there is no clear winner in terms of sustainability, esthetics, biology and function. Both solutions require a perfect synergy of all the fields of specialties involved and the treatment steps to achieve the optimal result for the individual patient.

Acknowledgements

The author would like to thank Dr Tidu Mankoo for the systematic and thorough editing of the whole essay, Dr Frank Paqué for his support in the discussion of the endodontic aspects, and Walter Gebhard and Nic Pietrobon for their contribution in creating the dental ceramics.

References, Part 2


