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Apical termination of root canal procedures—ambiguity or disambiguation?

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Abstract

The issues of working length determination, its apical extent, and the position of the final root canal filling have been controversial, as differing points of view have existed between the biologically based and clinically based endodontic gurus regarding this concept for decades. Coupled with the following issues, it has become somewhat of an empirical bastion for clinicians, especially those in the limelight or who use social media to augment their clinical prowess: (1) the variable anatomy of the root apex; (2) where to terminate canal enlarging and shaping apically; (3) status of the accessory communications apically; (4) size of the apical preparation; (5) ability to debride the apical extent of the root canal and remove both bacteria and biofilm; (6) response of the periapical tissues, when both vital and necrotic, to the intracanal filling materials and techniques that may impinge on these tissues; and (7) long-term outcomes and assessments of the procedures rendered. For purposes of succinctness, the concept of working length, the apical position of instrument termination, and the position of the final filling will be addressed simultaneously in this paper.

Beyond the apex—danger lurks

Cravens JE. Immediate root filling. Trans Ill State Dent Soc—29th Annual Meeting, The Dental Review Co., HD Justi & Son 1893;45–59.

Introduction

One could consider using a systematic review to try and answer the controversial challenges cited in the abstract; however, this approach would not work historically, and from a contemporary standpoint, so very few, if any, published studies qualify to fit into the higher levels of the hierarchy of scientific evidence that the essential issues would not be addressed (Gutmann & Solomon 2009). Therefore, a somewhat unorthodox approach to this concept has been chosen, one in which historical reflection and contemporary assessment will be used to compare and contrast philosophies that address the issues of concern. The starting point will be the First International Endodontic Conference that occurred in Philadelphia, PA, USA, in 1953.

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Review

Codification of the principles of root canal procedures

Up until the First World Conference on Endodontics was convened by Dr. Louis I. Grossman (Fig. 1) during the week of June 22, 1953 (Grossman 1953), multiple treatment parameters were being used daily by clinicians and different philosophies of treatment were being espoused in dental education around the world. Primarily, teeth were being extracted as opposed to addressing the many challenges of root canal procedures due to the overwhelming impact of the focal infection theory, along with the apical anatomical challenges that had been highlighted in the first part of the 20th century.

While not a recognized specialty of dentistry globally at that time, endodontics and the provision of root canal procedures had been advocated routinely in some, very limited, and visionary areas of dentistry, even with the name of endodontia being proposed by Dr. H. B. Johnston and accepted by the community at large, including the American Association of Endodontists (Gutmann 2008). However, this first world conference established some significant guidelines for clinical procedures based on historical documentation and treatment philosophy up to that point, both clinical and biological. It is here that this manuscript will begin to explore the issue of working length in an attempt to clarify all aspects of the

Fig. 1 Dr. Louis Grossman—reproduced from the University of Pennsylvania 1943. (http://www.aae.org/welcome/0207pulp.html)

challenges involved in apical biology in relation to a preferred termination point for root canal procedures.

What were the important outcomes of this first conference?

While 21 principles of treatment parameters were forthcoming, two very specific guidelines emanated from the presentations and deliberations from a multitude of international experts, in particular Drs. Louis I. Grossman, Lester B. Cahn, and Ralph Sommer from the USA, Dr. Francisco Pucci from Uruguay, Dr. Birger Nygaard Ostby from Norway, and Dr. George C. Hare from Canada. These two principles were as follows:

1. Traumatic injury to the surrounding (periapical) soft tissue should be avoided at all times. To this end, instrument stops should be used and instruments should be confined entirely within the root canal (Grossman 1953).
2. "…the canal filling should seal the apical foramen, and that if the apical millimeter or so of the canal is filled with healthy living tissue, the root canal filling should terminate at this level rather than at the apical foramen" (Grossman 1953).

What was important at that time was the fact that dentistry and endodontics were still struggling with the vestiges of the "focal infection theory" (Grossman 1925) that had been smoldering through various levels of conflagration since 1900 (Hunter 1900) but was brought to a crescendo by William Hunter's (Fig. 2) diatribe against the dental profession during his classic presentation "An Address on the Role of Sepsis and Antisepsis in Medicine" that was delivered to the Faculty of Medicine of McGill University in Montreal in 1910 and published in 1911 (Hunter 1911). Advanced further by Billings (Billings 1916) and Rosenow (Rosenow 1919), and perpetuated by others at that time (Grieves 1914a; Grieves 1914b; Grieves 1920), this concept impacted greatly on tooth retention. If tooth retention was deemed possible in the presence of a questionable pulp or a tooth with a periapical lesion, what treatment parameters may be considered as both acceptable and successful? Therefore, the issues addressed and the principles put forth from this conference had to be carefully analyzed and biologically sound. To that end, some of the following questions could be asked retrospectively:

- Historically, what contributed to the thinking that helped to solidify these principles?
- What was it about the biology of the periapical tissues and the clinical techniques at that time that led to this definitive position?

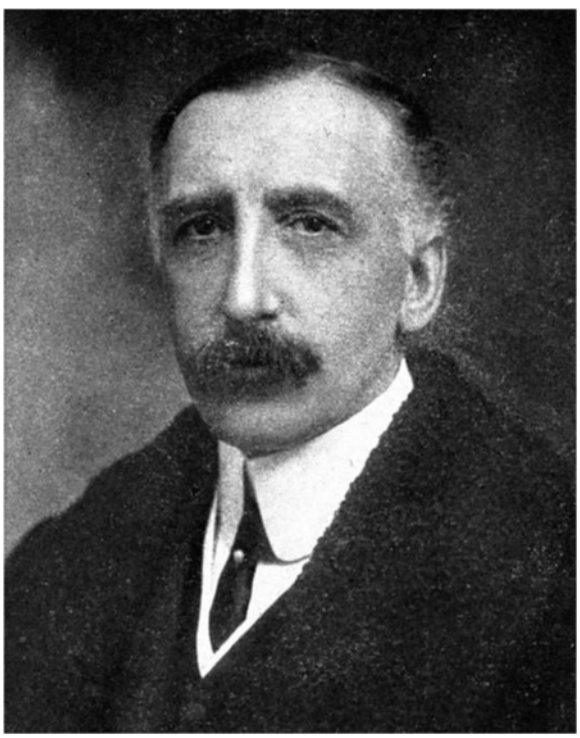

Fig. 2 Dr. William Hunter—reproduced from Bremner MDK. The Story of Dentistry, Dental Items of Interest Publishing Co., New York, 1939. Also found in Dent Cosmos 1934; 76(1):19

- Was this approach to managing the apical portion of the root canal and root apex to be the same in teeth with viable apical tissues or necrotic apical tissues with or without the obvious presence of an apical rarefaction?
- Was the best evidence available to the individuals in this conference? What role did apical resorption play in these guidelines, if any?
- What was known about the root apex in 1953 that was not known in 1911 or before?
- What was known about treatment outcomes in 1953 relative to current practices at that time and previous practices that may have impacted on tooth retention or successful outcomes?

Historical gleanings

A sense of respect for the apical constriction in the roots and the periapical tissues during root canal procedures already appears in the mid-1800s, when Dr. Harwood of Boston had communicated with Chapin Harris (Fig. 3), one of the co-founders of the first dental school, the Baltimore College of Dental Surgery, Baltimore, MD, USA, his considerations in the operations of cleaning the root canal of its pulp tissue (Harris 1855).

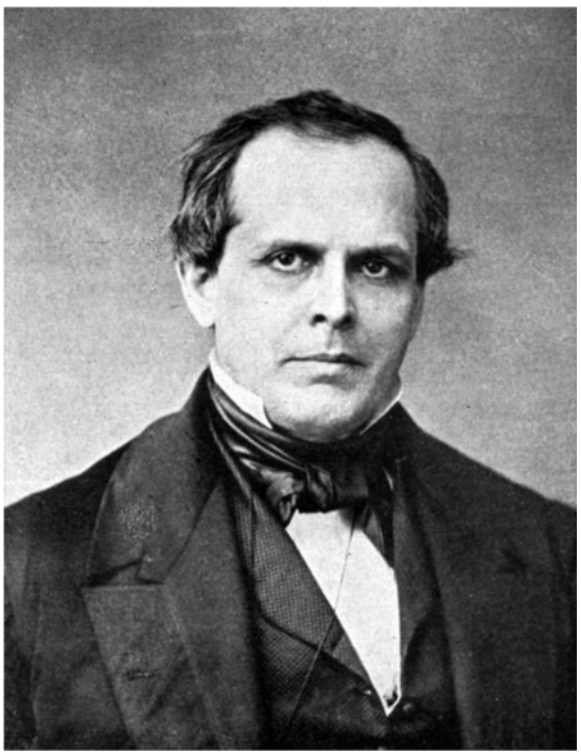

Fig. 3 Dr. Chapin Harris—reproduced from Prinz H. Dental Chronology, Lea & Febiger, Philadelphia, 1945

> It should be borne in mind, that at the point where the vessels and nerves in question enter the root, the passage is much smaller that it is immediately within. This strait (constriction) will be easily recognized when reached, by the touch, the instrument appearing to be arrested by an obstacle, and not by being wedged in a narrow passage. Care should be taken, I think, that the instrument is not allowed to pass through the strait, either by being too small or by being revolved there till it cuts its way through. For, by wounding the parts without the tooth, and forcing particles of bone (dentin) out upon the parts external to the roots, the danger of an unfavorable result would be greatly increased. (Harris 1855)

Subsequently, Edmund Noyes of Chicago noted that:

> …the treatment of pulps was not seriously undertaken by the profession previous to 1865, and that after 1870 the attempts to save teeth with exposed living pulps, or with dead pulps, became quite common practice, the method generally employed being the removal of the contents of the canal and placing of from one to many treatments of creosote on cotton, most operators leaving such a treatment as a root filling. (Noyes 1922)

Little change in this philosophy existed until the late 1800s and the early 1900s, at which time the playing field was identified as being far more challenging due to studies on the root apex anatomy and apical root canal that proliferated at that time (Fischer 1909; Preiswerk 1912; Hess 1917; Grove 1916; Noyes 1921) (Fig. 4). First, recognizing the fact that there were significant apical ramifications led dentists to performing many procedures that only resulted in the removal of one half to two thirds of the dental pulp (partial pulpectomy) (Davis 1923);

> It is our practice at this time to amputate large pulps somewhere in the apical third of the root. With small canals, as in the buccal roots of upper molars and the mesial roots of lower molars, we have been excising at the floor of the chamber… (Davis 1923);

leaving challenges of the unpredictable apical anatomy to normal healing processes; or focusing on the use of substances such as arsenic to "sterilize" the retained apical pulp tissue and kill bacteria or tannic acid to form an albuminate of tannin, which was insoluble and prevented tissue disintegration (Mills 1897):

> …where we cannot (reach the apical foramen), as in contracted or tortuous root canals, we force tannic

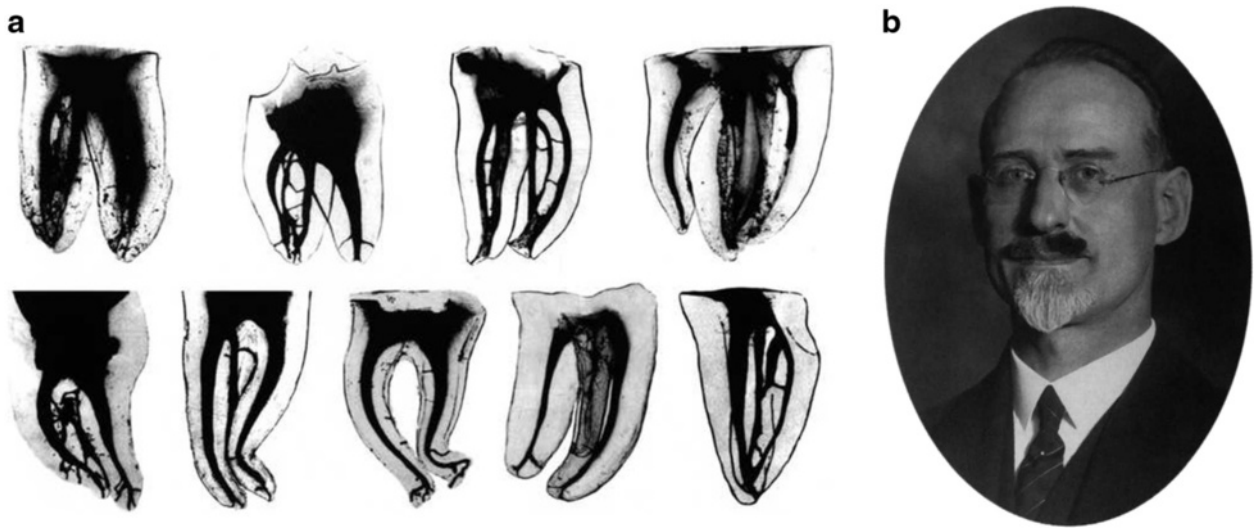

Fig. 4 a Tooth anatomy depicted by dye penetration. From the work of Oskar Keller, Anatomie der Wurzelkanäle des menschlichen Gebisses nach dem Aufhellungsverfahren. Zürich, Buchdruckerei, Berichthaus. 1928. Keller was a protégé of **b** Dr. Walter Hess—reproduced by permission of Nicola Perrini owner of the collection from Fondazione Castagnola that are found in Storia anatomica del sistema dei canali radicolari. Società Italiana di Endodonzia, 2010

> acid solution into the inaccessible pulp tissues…we used the tannic acid solution because when brought into contact with any remaining pulp tissues in the root canal, it forms an albuminate of tannin; a compound which is insoluble in any of the fluids of the surrounding tissues, and consequently no disintegration can take place to cause any after trouble. (Mills 1897)

The challenging nature of the apical root anatomy was presented most vividly by Guido Fischer in 1907 (Fig. 5) when he started his large-scale research, with a new method in looking at human and animal root canals, paying special attention to their thin ramifications and apical terminations (Fischer 2010) (Fig. 6a–c). Fisher divided the different morphologic variations of the pulpal cavity into:

- Simple ramifications or branches and lateral canals within the radicular dentin
- Intercommunicating canal system
- Islands of hard tissue within the canal

These differentiations were named as bifurcations and ramifications, which created a complex system of apical morphology. With his method, Fisher established the accurate morphologic variations of a developing tooth, either in physiological or pathological conditions. He described very accurately the neoformation of dentin and pulpstones within the root canals. Furthermore, by associating macroscopic and microscopic observations, he showed how the root canal morphology is very complex

Fig. 5 Dr. Guido Fischer—reproduced by permission of Nicola Perrini owner of the collection from Fondazione Castagnola that are found in Storia anatomica del sistema dei canali radicolari. Società Italiana di Endotonzia, 2010

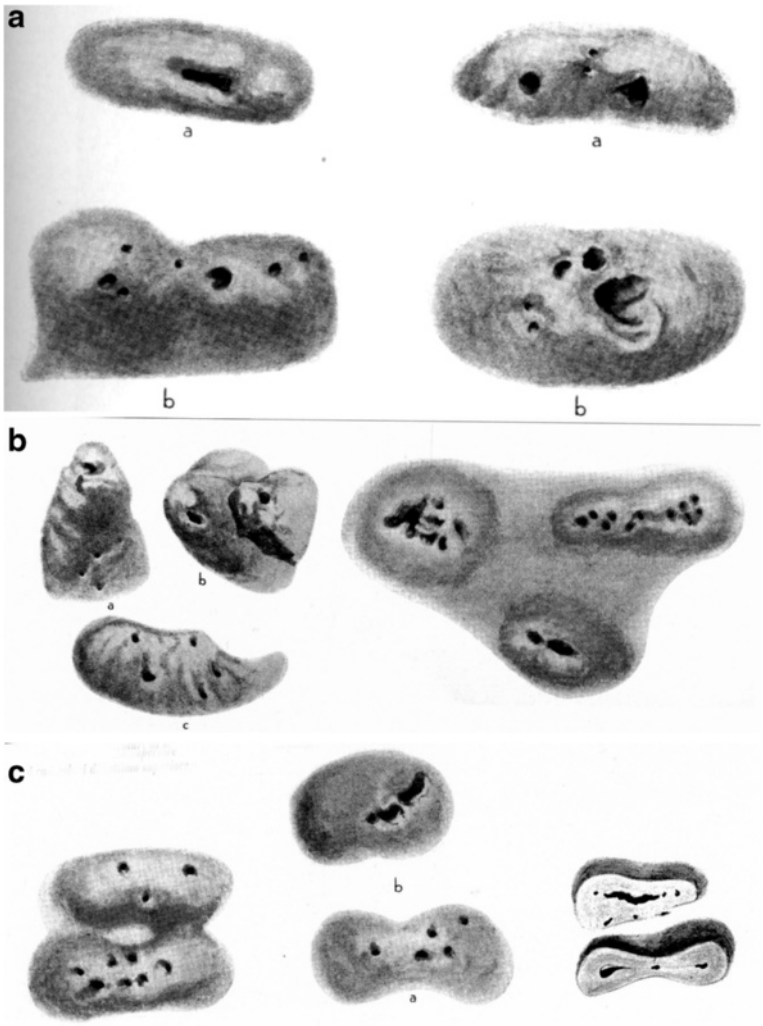

Fig. 6 Apical ramifications as described by G. Fischer: **a** second premolar, **b** first maxillary molar, **c** second maxillary molar. Bau und Entwicklung der Mundhöhle des Menschen unter Berücksichtigung der vergleichenden Anatomie des Gebisses und mit Einschluß der speziellen mikroskopischen Technik. Leipzig; Verlag von Dr. Werner Klinhardt, 1909

due to the ramifications present, calling them lateral canals (Seitenkanal), and also apical ramifications called regio ramificatoria, which is referred to presently as an apical delta. The complexity and inability to predict the canal morphology brought him to name the whole system as the radicular canal system (Kanalsystem).

Subsequently, there began a true appreciation for the nature of the tissue at the end of the root, as histological studies were able to demonstrate that the pulp tissue ended at the dentinal-cemental junction and that there were few if any incidences of pulp tissue going all the way to the end of the root or to the extent of the major foraminal opening (Grove 1916; Noyes 1921). The issue now was the clinical management of these tissues.

According to C.J. Grove, "It should be remembered that the apical foramen of fully developed teeth is formed by the cementum. If the pulp tissue were present in this portion of the canal, dentin should be formed by the odontoblasts in the pulp tissue. I believe the fact that this does not occur clearly indicates the erroneous character of the theory that the pulp extends through the foramen." (Grove 1916). It is here that this author asks one of the most crucial questions that the present manuscript is attempting to address: "The question now confronts us, What shall be done with these tissues when the pulp is devitalized?" (Grove 1916) (Fig. 7).

Key investigators, such as Noyes (Noyes 1922; Noyes 1921), Grieves (Grieves 1915; Grieves 1919), Blayney (Blayney 1927; Blayney 1922; Blayney 1926; Blayney 1940; Blayney 1932; Blayney 1936; Blayney 1929a; Blayney 1929b), Skillen (Skillen 1922), Hatton (Hatton 1922), Coolidge (Coolidge 1921; Coolidge 1922), Groves (Grove 1921; Grove 1931), and Davis (Davis 1922a; Davis 1922b), recognized these anatomical challenges, including that of

Fig. 7 Histological view of the root apex with root canal filling terminating 2–3 mm from the end of the root. Note the tissue below the root filling is periodontal in nature and the walls of the canal in this area are covered with cementum. There is also a hard tissue barrier that has formed adjacent to the root filling that may have been induced by dentin chips or represents an osteocemental response. This presentation amplifies the fact that in many teeth the pulp and pulpal canal terminates far above the anatomical root end

cemental permeability, especially in light of the focal infection theory and still approached teeth with compromised or necrotic pulps with the same focus, "Shall we, or shall we not, attempt to retain the pulpless tooth? In the presence of the irrefutable dictum that the natural organ is better than any substitute, the answer is 'We shall.' Noyes said it succinctly; '…let us rather make it a practice to extract only such teeth as diligent, conscientious and persistent effort have proven conclusively to be beyond our present ability to put in wholesome, safe condition.'" (Noyes 1921).

In 1929, Blayney published his results on 10 years of making histological analyses of root ends from extract teeth that had been root treated. He had several thousand teeth in his history profile but chose to examine histologically 250 of these teeth, some of which were extracted shortly after treatment due to a diagnosed failure, while others had been in the mouth for a number of years (Blayney 1929b). Very early on in his study, he realized that "it was unusual to find a root-end with but a single apical foramen." His conclusions strongly suggested that:

"1) The dental pulp may be removed without causing irreparable damage to the periapical tissues, provided the following definite plan of operation is carried out: a) surgically clean technic ; b) use of only mild antiseptics, all caustics being eliminated; c) avoidance of injury to soft tissue in the apical foramina; d) removal of all true pulp tissue; (and) e) filling of the canal with a bland, non-irritating, non-absorbable filling material to near the site of amputation.
2) Following the operation, there is begun, in the apical region, a process of resorption that enlarges the apical foramen, or a new channel may be cut that more successfully meets the conditions within the canal.
3) These resorptions may heal, with the formation of calcified material resembling cementum.
4) Many of the apical foramina may be reduced in size by repair calcification. But this reduction seldom obliterates the canal. as sufficient space usually remains for an efficient circulatory apparatus.
5) The filling material, when in contact with soft tissues, excites a foreign-body reaction. Better results are obtained in the cases that are slightly underfilled." (Blayney 1929b).

Similar findings were identified, and clinical techniques to achieve these results were supported by a multitude of individuals during that era. As early as 1922, Noyes echoed these same directives as follows; however, he was also concerned with root fillings that were too short (Noyes E 1922):

> There is one more thing I want to say in regard to these fillings that do not reach the ends of the canal. It is my belief that we should in every case, wherever we can possibly do so, get our filling to the end of the PULP CANAL (Author's Emphasis). In every one of those cases in which I did not get there, you may depend I spent an hour or more, may two or three, in trying to get there. But the point I want to make particularly is that we may ignore absolutely the foramen through cementum if we can fill the pulp canal to the end of the dentin. While you cannot fill a minute foramen, which is as fine as a hair in some cases, in my judgment a tooth is three or four or ten times as safe if you fill the root to the end of the pulp canal, leaving the fine foramen through the cementum

of the root without meddling with it, as it would be if you drilled through the foramen and carried the filling to the end of the root and put a cape over the end of it, as Dr. Rhein advocates. (Fig. 8) (Author's note: Dr. Rhein advocated filling beyond the end of the root so the filling material would encapsulate the apical 2–3 mm, thereby sealing off all the accessory communications. He referred to this as "mortarization" of the root end.) (Fig. 9)

However, Dr. Rhein had different opinions regarding root canal therapy that stood in opposition to the mainstream clinicians at that time, regarding procedural accomplishments (Rhein 1920):

> The question of root-canal therapy is one that embraces a very particular point, and that is, there is no question that I know of, as a medical man, outside of brain surgery, (and I would even include a large amount of brain surgery) that requires the same amount of skill, patience and time…When I show hundreds of roentgenograms - some of them dating back to work done almost 30 years ago (Author's note: which would be in the late 1890s), showing absolutely, so far as a roentgenogram can show, normal tissue (with) thorough encapsulation of gutta percha on the apices of the roots - I definitely refute the essential point of criticism of the essayist's paper. (Rhein 1920) (Author's note: that root canals should only be filled to the end of the dentinal canal and not impinge on the cementum).

Fig. 8 Dr. Meyer L. Rhein—reproduced from J Dent Research 1933;13:100

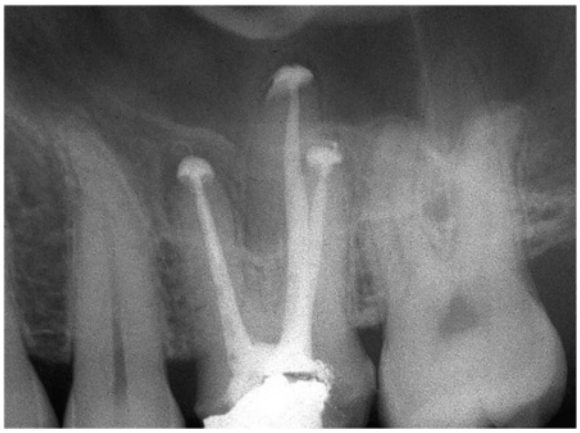

Fig. 9 Maxillary molar that has root filing beyond the end of the root that encompasses the root-end anatomy, as proposed by Rhein with his "mortarization"

To rationalize his technique of encapsulation even further, Dr. Rhein indicated that:

> Where I have found re-infection in my own cases and have had to extract teeth, I have also found invariably extra foramina at some point that had not been encapsulated, and which were the cause of the recurrence of infection. (Rhein 1920)

The issue of necrotic remnants being left in apical accessory canals and treatment failure still reverberates in today's clinical practice and provides the impetus for the promotion of filling to the root apex, using a technique in which these canals may be filled. However, this achievement may be flawed with regard to histologically identified outcomes (Ricucci & Siqueira 2010).

Interestingly, Grieves had fostered directives similar to Blayney as early as 1914–1915 relative to the importance of periapical pathosis, cemental repair, and apical healing in the presence of the apical ramifications (Grieves 1914a; Grieves 1914b).

> There is some evidence for believing that remaining vessels and apical pulp-shreds, lying in touch with surrounding vascularity, either become organized into fibrous tissue or foramina are closed by deposits of cementum or osteo-dentin. This can occur only in a vital apex, not infected, nor saturated with chemicals, nor PERFORATED AND OVER FILLED (Authors' Emphasis); and only in one to which the

periodontium is physically attached. However, he goes on to say, in his extensive treatise, "The vital apex is, thus, the crux of all canal operations. Its maintenance is worth any amount of time and effort. It cannot be encapsulated (Author's note: as per Dr. Rhein) because periodontal fibers are everywhere attached to it. There is, therefore, no denudation or hypoplasia in which encapsulations may lie, unless they traumatically protrude into the membrane, granulomata, or cysts. Quite the reverse: the denuded apex, necrotic by whatever means, is not worth a moment's effort, no matter how medicated nor how well filled (Author's note: this reflects the impact of focal infection). One of the gravest mistakes of dentistry is the stubborn belief that correct root-canal filling will cure apical disease." (Author's note: this same concept is present today when clinicians say they are treating periapical lesions or apical periodontitis) The most perfect canal operation is never curative, but only a preventive procedure. (Grieves 1920)

Quite vocal in this controversy of where to terminate the root canal filling and the issue of retaining pulpless teeth was Dr. Rodrigues Ottolengui (Fig. 10) of New York City (Ottolengui 1922):

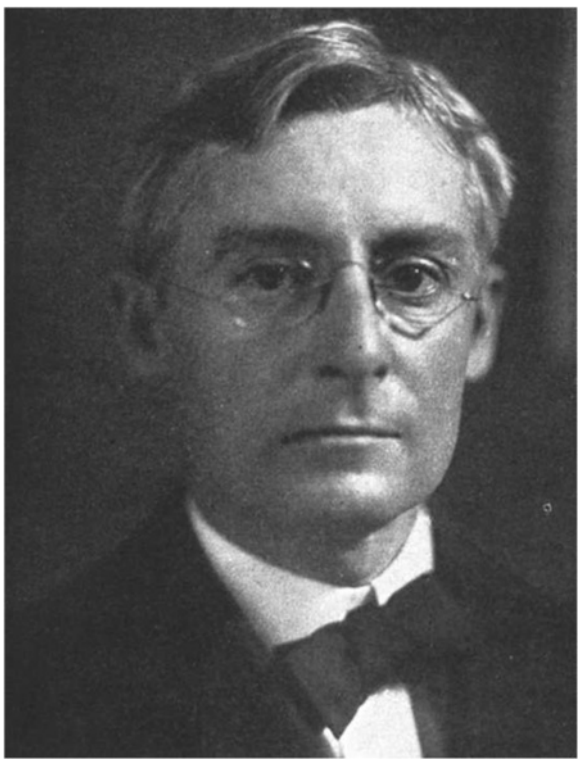

Fig. 10 Dr. Rodriguez Ottolengui—reproduced from Prinz H. Dental Chronology, Lea & Febiger, Philadelphia, 1945. Also found in Dent Cosmos 1934; 76(1):158

There be dentists who conscientiously believe that a pulpless tooth is a dead tooth; that every dead tooth is doomed to infection; and that all infected teeth are a menace to the health of the individual. to such practitioners this communication is not addressed. There be others who believe that a pulpless tooth may be so treated that it will not only be tolerated by the human body, but may be made to serve its function of mastication, and aid in the initial step of digestion, thus becoming an important factor in metabolism and an ultimate contributor to the health of the subject. From such as subscribe to these tenets I crave attention, trusting that I may deliver to them a message which may in some small degree render their efforts to minister to suffering humanity more certain and more effacious. (Ricucci & Siqueira 2010)

To do so, Ottolengui dictated his doctrines for root canal filling procedures (Ottolengui 1922):

"1. Any radiographic evidence of gutta percha beyond the apex of the root, is a protrusion of the filling material…
2. The protusion of gutta percha beyond the apex demands space for its occupation.
3. …any appearance of gutta-percha beyond the apex of a healthy root is an evidence of a fault in the technique.
4. In the presence of infected apical areas…and the gutta percha has been forced beyond the apex… whether such infection, both of the area and of the protruding foreign body can be overcome, will be determined solely by the vital responses of the patient in each instance. Sometimes a cure will be accomplished in spite of the gutta percha. It is inconceivable, however, that the protruded material can act as a curative factor." (Ottolengui 1922)

Transitions in thought and reaffirmation of clinical directives

In the late 1930s, Dr. Bernhard Gottlieb (Fig. 11) published a monograph entitled "Dentistry in Individual Phases" (Gottlieb 1938). In this monograph, he discusses the challenges that are present in dealing with root canal procedures, i.e., instruments and medicaments, that may come in contact with the periapical tissues during treatment. He indicated that he had no concept as to the response of these tissues to the treatment procedures, while at the same time hoping to control any inflammatory responses that may prevent healing with calcified tissues. To these purposes, he used a dog model in his investigations:

Fig. 11 Dr. Bernhard Gottlieb—reproduced from Gutmann JL. Bernhard Gottlieb's impact on contemporary endodontology. J Hist Dent 61:(2)85-106, 2013. Erratum 61:(3) 128, 2013. (http://www.alumni-meduniwien.at/news/medizin+im+bild/bernhard+gottlieb). (http://www.alumni-meduniwien.at/news/medizin+im+bild/bernhard+gottlieb)

> …in the case of extraction of the pulp it was or importance to establish, how any given method would operate when the pulp canal was in direct connection with the periapical connective tissue. In the case of the dog, on account of its ramifications the pulp tissue is without exception separated from the connective tissue, so that no connection is established with the periapical connective tissue throughout the manipulation in the canal. We now had to drill through the tooth to this area, and at once it was evident that we must use a much more pretentious method, if we are to come in direct contact the periapical tissue and if we were to care for injuries to the connective tissue. This change made in the procedure of the experiment by this drilling was necessitated by the fact that in the human mouth it was not at all uncommon to come in contact with the periapical connective tissue during pulp extraction. (Gottlieb 1938)

Gottlieb understood the challenges faced with human teeth that required the removal of a viable dental pulp, but he also realized the importance of this same set of clinical circumstances in the presence of an infected pulp or necrotic pulp:

> The claims that we had to satisfy in the treatment of a periapical focus of infection took an a much more complicated form, and aspects developed that we could in nowise anticipate. We could form no clear picture of what happened to the necrotic root surfaces, nor could we imagine what might be expected from branchings of the root canals that harboured dead tissue. It was demonstrated that soon after sterilizing and freeing these dead tissue of germs, the neighbouring inflamed connective tissue regained health, and almost at once deposited cementum upon the necrotic surfaces of the tooth. This cementum may also close up the apical foramen, and thus produce a complete surface consisting of living cementum, which removes completely every doubt concerning retention of such a tooth. (Gottlieb 1938)

In his assessment, Gottlieb defies the tenets of focal infection, indicating that properly performed root canal procedures, with retention of root-filling materials inside the canal in the presence of a necrotic pulp, will result in biologic healing of the periapical tissues and the formation of a cementum closure of the canal apically (Fig. 12). Furthermore, he was quite adamant about where to terminate these procedures, especially in the presence of a vital, yet possibly inflamed, pulp, indicating that "surgical common sense forbids it" (that is, going past the apical foramen). He indicated that there are healthy tissues at the point of severance apically, and therefore, the use of caustic drugs was prohibited, files must not penetrate the foramen (present day concept of patency filing), and any damage to the periapical tissues may well prevent the healing of these tissues with the cementum (Davis 1923). He published his findings in 1928 and presented them at the 8th International Dental Congress—FDI in 1931 in a special session that featured world-class authorities who addressed the controlling of root canal treatment procedures (Gottlieb et al. 1928):

> Once a piece of foreign material has penetrated through the foramen, no favorable condition of any kind can induce the closure of the entrance by the formation of a hard wall. (Gottlieb et al. 1950)

Gottlieb's philosophies went far beyond where to terminate both instrumentation and obturation. Being one of the stalwarts from the Vienna School of Medicine, who came to the USA (Gutmann 2013; Kremenak &

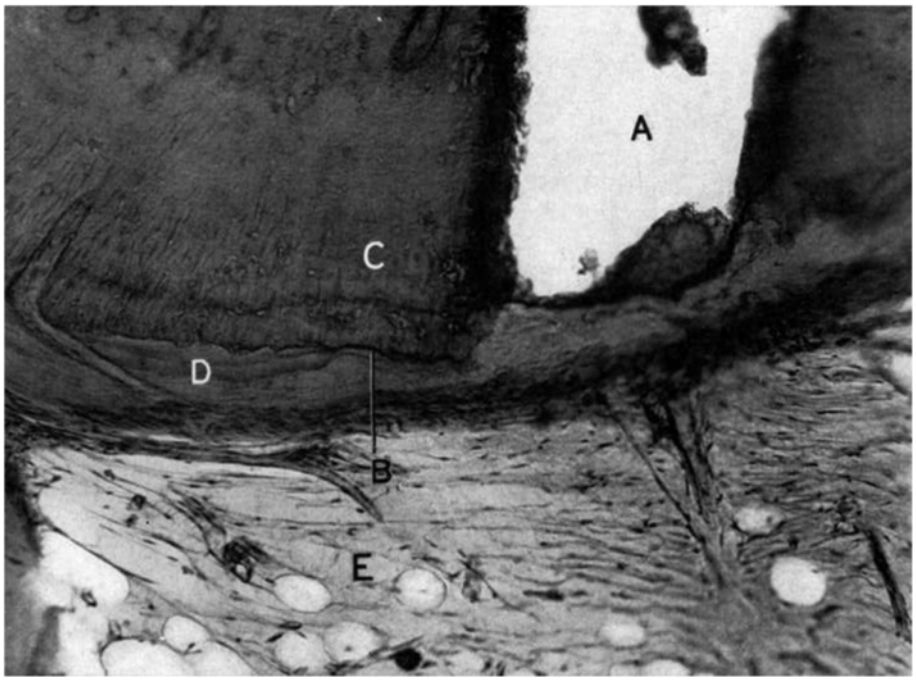

Fig. 12 Root apex showing cemental coverage following root canal procedures and subsequent healing. *A* represents the root filling; *C* is the original cementum, while *D* is the new cementum; *B* is the junction of the two tissues; and *E* is the inflammation-free periodontal ligament. Gottlieb B. From data accumulated on Professor Gottlieb from the Gottlieb Collection presently located at the Baylor College of Dentistry, Dallas, TX

Squier 1997), his focus in dentistry was highly biological and he devised a method to ensure the development of hard tissue (cementum) at the root apex following root canal procedures. His method to achieve apical healing with cementum was simple. He used dentin from teeth that had been ground fine and sterilized. After mixing the dentin powder with sulfathiazole or restorative cement, it was applied to the apical portion of the root canal prior to obturation. The success of his approach was demonstrated in an animal model (Fig. 13) and

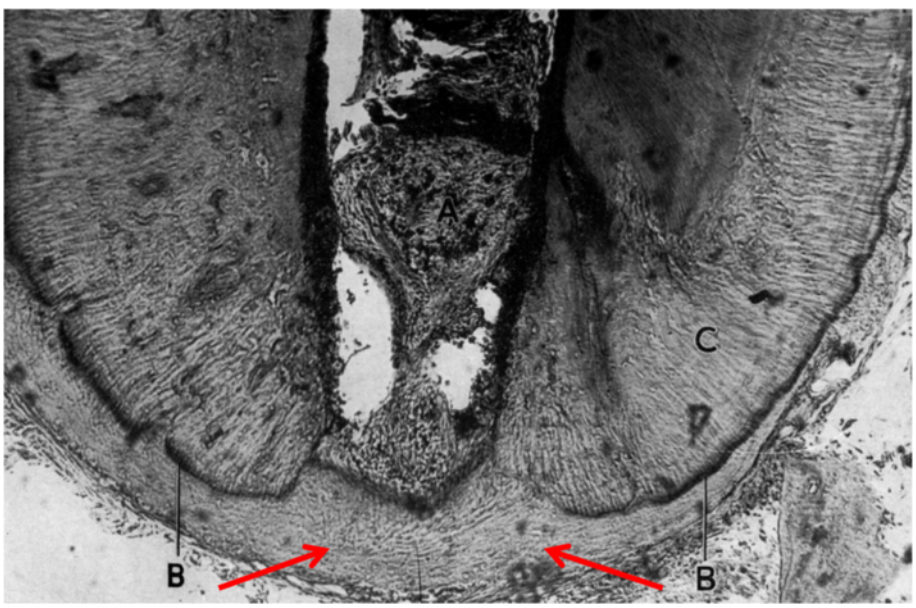

Fig. 13 Healing at the root apex with cementum following the use of a dentin-cement root canal filling in the apical portion of the root. Gottlieb B. From data accumulated on Professor Gottlieb from the Gottlieb Collection presently located at the Baylor College of Dentistry, Dallas, TX

clinically was advocated for patient use in his monograph published in 1938 (Gottlieb 1938). Although not having the molecular biological investigative capabilities available today, Gottlieb's concept was to induce healing through the use of substances (calcium salts and protein matrices—for which the dentin was not to be sterilized with heat to prevent the destruction of the proteins) within the dentin, which today we now know as specific growth factors, such as bone morphogenic proteins, fibroblast growth factors, insulin-like growth factors, and epidermal grow factor, in addition to dentin matrix collagenous and non-collagenous proteins, such as dentin sialophosphoproteins, osteocalcin, bone sialoproteins, serine-rich phosphoproteins, dentin matrix proteins, and so forth, the latter of which has been identified in the induction of cementoblasts and the formation of cementum (Rutherford & Fitzgerald 1995; D'Souza et al. 1997). In essence, he had begun the concept of tissue engineering to promote predictable healing (regeneration) following root canal procedures. While some authors had identified other materials, such as ivory and bone powder for the induction of hard tissue, Gottlieb focused on dentin powder but indicated that there were two requirements for any material to be successful:

> …first, it must be resorbable, and second, it must stimulate the connective tissue to form new additional hard tissue which will replace it. (Gottlieb et al. 1928)

While the philosophy of using dentin chips packed in the apical preparation to enhance periapical healing with hard tissue formation was used by Göllmer (Fig. 14) in the 1930s (Göllmer 1936), and Mayer in the 1940s (Mayer 1949), its popularity dwindled until it was revived somewhat in 1967 by Engström and Spångberg (Engström & Spångberg 1967) and in 1978 by Tronstad (Tronstad 1978). Using monkey teeth, Tronstad found that a plug of dentin chips was well tolerated by the tissues, serving as an effective apical barrier. Further studies by Oswald and Friedman in 1980 demonstrated the presence of cementum formation with minimal inflammation in the apical tissues of the maxillary canines of cats (Oswald & Friedman 1980). To the contrary, however, Holland and co-workers found that the presence of dentin chips at the apical extent of the root canal in monkey's teeth did not influence healing (Holland et al. 1983), and in particular, when the dentin chips were infected, the outcome was totally unfavorable (Holland et al. 1980).

The philosophies of root canal treatment and where to terminate not only both enlargement and shaping but also obturation permeated the early 1900s in a plethora of published papers and dental meeting presentations. The biological principles of root canal procedures had been formulated, even to the point of enlisting "Mother Nature" to put the finishing touch on the treatment rendered (Fig. 15). Furthermore, they formed the basis for the principles that were developed at the First World Conference on Endodontics in 1953, as very little

Fig. 14 Formation of cementum sealing and healing of the root apical tissues following the placement of dentinal chips. Göllmer L. Die Wurzelfüllung auf Grund der preparativen Fähigkeit der Wurzelhaut (The use of dentin debris as a root canal filling). Ztschr f Stomatol 1936;34:761

Let Nature Fill Your Root Canals

Cross section lower bicuspid six years after pulpotomy. a—Cementum. b—Dentin. c—Adventitious dentin. d—Osteoid tissue.

It appears now that pulp canal surgery, all methods of which have heretofore proven faulty, is to be revolutionized by attacking the problem from a different angle.

Dr. W. Clyde Davis of the University of Nebraska, after a scientific study and exhaustive research of the subject, proves that the amputated pulp will heal with a connective tissue scar, which will gradually calcify, terminating in a complete ossification of the pulp, thus effectively filling the pulp canal.

Dr. Davis is writing a book, "Dental Pulps and Pulp Canals," which will be published, before its appearance in bound form, serially in

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Fig. 15 a Advertisement that appeared in Trans Ill State Dent Soc—29th Annual Meeting, The Dental Review Co., HD Justi & Son 1893 that extolled the value of normal healing with a connective tissue scar that will gradually calcify. This was placed to support Dr. W Clyde Davis's approach to "pulp canal surgery" that did not have a sound biological and clinical basis at that time; **b** Dr. W. Clyde Davis, archival print reprinted with permission from the American Association of Endodontists, from Milas, VB. A History of the American Association of Endodontists 1943–1968, General Printing Co. Chicago, 1968

changed in treatment parameters in the previous 40 years. Ironically, no mention of Gottlieb's efforts in promoting these biological principles were made at this initial conference in 1953, and his contributions to the principles of endodontics were not even recognized. Even though he had provided significant research to support the science of endodontics (endodontology), there is no mention of him in the early 1940s during the organization and formation (originally the American Root Therapy Association, which became the American Society of Endodontists) of the present day American Association of Endodontists (AAE) (Milas 1968). Ironically, Gottlieb's student and colleague, Balint Orban, was the first editor of the Journal of Endodontia in 1946, which was the initial and official voice of the organization that became the AAE.

Enter empiricism as the endodontist's mantra

In 1953, an article was published by Bernard Berg that served as the basis for new concepts in root canal preparation that focused on the importance of canal shaping along with thorough obturation *to* the root apex (Berg 1953). There was no discussion of where to terminate activities in the root canal other that at the root apex. The concepts within this publication served as the basis for the principles that were extolled by Dr. Herb Schilder 14 years later in 1967, in his seminal publication on canal obturation (Schilder 1967) and in 1974 on cleaning and shaping the root canal system (Schilder 1974). Regardless of all the research that had been done on the biological ramifications of the position where to terminate both the canal preparation and obturation in the early part of the 20th century, neither author provided any references to the *empirical claims* that were made regarding the instrumentation techniques proffered within these publications. When it came to obturation, the publications by the latter author questioned the importance of the vertical extent of the filling material, focusing more on the concept of "three-dimensional filling." He even went so far as to refer to the cementodentinal junction as being the "theoretical…point which divides the pulp tissues from the tissue of the periodontal ligament," a concept that had been affirmed histopathologically for decades (Grove 1916; Noyes 1921).

While recognizing that filling to the theoretical apical end of the root canal was the point that may best encourage a physiological closure with cementum, that doing so "is not an unmixed blessing" due to the great degree of variability that exists in this anatomical location. Furthermore, he claimed that

> …the closure of the root end with cementum, while both possible and desirable, is demonstrable much more readily in animal experimentation that in human patients, and is unnecessary for the health and function of the apical periodontium. (Schilder 1974)

Rather than acknowledging that cemental deposition played a role in histological healing, closure, and sealing of the root canal system and clinical success, Schilder chose to relate the clinical success achieved to his philosophy of three-dimensional obturation:

> The enormous success which has followed filling root canals to their radiographic apices or beyond has led some to theorize that healing of large periapical radiolucencies may be stimulated by root canal filling material outside the confines of the canal. While this may be possible, it is more likely that, as in the case of filling to the cementodentinal junction, continued success results from the thoroughness of the three-dimensional filling along the major extent of the root canal and not on the fractional overextension or underextension of the filling. The wise old suggestion to slightly underextend root canal fillings in case of vital extirpation and to fill to the radiographic apex or slightly beyond in cases of pulpal necrosis and gangrene is probably more meaningful in terms of patient comfort that in terms of the ultimate result. (Schilder 1974)

In many respects, these empirical comments cast a dark shadow on many years of histopathological research and in-depth investigations by the few biologically motivated clinicians who fought the fight against both focal infection and the inadequacies that permeated clinical practice. In doing so, this ushered in the "look or thrill of the fill" on the two-dimensional radiographic, and as long as the filling material was positioned at the extent of the root, and one or more accessory or lateral canals evidenced some type of filling with puffs or buttons of sealer or gutta-percha along the root surface, success was considered inevitable and the focus of treatment was on new instruments and new techniques.

Ironically, Schilder's article on obturation was published 7 years prior to his paper on cleaning and shaping of the root canal. In this latter publication, he does address the issue of apical termination of the root canal preparation and filling:

> …it will be understood that the instruments are, in most cases, slightly beyond the confines of the root canal in the adjacent periodontal ligament space. This position will be reached from time to time with appropriate caution, to ensure both a complete debridement of tissue debris and to maintain the patency of the canal. Deliberate instrumentation short of this point without occasional probing of the apical opening predisposes to dentin mud accumulation at the apex, thereby increasing the risk of inadvertent blockage of the primary canal. This major source of frustration for inexperienced operators can be avoided by probing to or near the radiographic apex sufficiently often to keep dentin mud from accumulating there. (Schilder 1967)

This was the first indication that "patency filing" was being advocated over attempting to retain instruments within the "pulp canal," while other authors who recognized the possibility of packing debris and dentin mud advocated apical clearing without going beyond the confines of the pulp canal (Walton & Torabinejad 1989).

In the late 1980s, due to the plethora of advances in enlarging and shaping techniques and enhanced instruments and the focus on a more thorough cleaning of the root canal system, patency filing was advocated as a routine clinical procedure (Buchanan 1989), albeit empirical, which gained acceptance, especially in many of the dental schools in the USA (Cailleteau & Mullaney 1997). Claims were made that the removal of accumulated debris in the apical portion of the canal was essential for both cleaning the apical foramen and ensuring success through a more thorough canal obturation. Since then, while there have been numerous publications that have addressed the value of this procedure, it has been accepted globally by many with the exception of the some areas in Northern Europe and Scandinavia (Goldberg & Massone 2002; Cemal-Tinaz et al. 2005; Araújo Souza 2006; Gonzalez Sanchez et al. 2010). In a recent randomized controlled trial that addressed the effect of maintaining apical patency on post-treatment pain in posterior teeth with necrotic pulps and the presence of apical periodontitis, no significant differences were noted between patency filing and no patency filing (Arora et al. 2016).

Contemporarily, four philosophies tend to permeate the clinical world of endodontics regarding where to terminate enlarging, shaping, and obturation: (1) those

based strictly on the anatomical studies; (2) those based strictly on prognostic studies and outcomes of treatment; and (3) those based on empirical directives… "it works for me." Using one of these first three positions as arguments, it is conceivable that every endodontist or dentist who performs root canal procedures can use all three for a given case or a selective, whichever was convenient, to exercise cognitive dissonance (Seltzer & Bender 1965). According to Simon and associates, "…differences represent conflicting opinions concerning the apical limit of preparation and overall differences in concepts." (Simon et al. 2009). Possibly the most influentional concepts within this dilemma of where to terminate both the enlarging and shaping and obturation lie in the status of the dental pulp at the time of the procedure. However, even this can create consternation due to the inability of the clinician to determine without question the viability of the dental pulp and/or the mere presence of bacterial species or bacteria and their associated biofilms, along with the location of such. Finally, (4) those based on the status of the dental pulp and periapical tissues may be the determining criteria for many clinicians, but the exactness of such is severely wanting.

Anatomical studies

The anatomical findings apically have been enhanced tremendously with the advent of micro-CT and SEM. The ability to view in depth the apical variations and challenges presented has opened a whole new world of appreciation regarding the issues that this anatomical region poses for the clinician in all phases of treatment (Figs. 16 and 17). This is especially true in not only the unusual morphological variations but also the presence of bacterial species and their accompanying biofilms (Siqueira & Lopes 2001; Richardson et al. 2009). These findings, if studied further, may result in an alteration of techniques to better determine working length and position of the canal material apically. While electronic apex locators have enhanced the procedures of working length determination (Simon et al. 2009; Martins et al. 2014), they cannot account for the high variability that is present apically (Figs. 18 and 19). Furthermore, additional definitive research most likely may result in newer, more biologically formulated materials for root canal obturation. Moreover, the anatomical findings with the new technologies have provided a better understanding as to why both biologically based and clinically based treatment parameters of treatment may fall short of ideal in many cases.

One of the more interesting publications (two parts) that addressed the focus of this paper appeared in 1998, before the availability of micro-CT (Ricucci 1998; Ricucci & Langeland 1998). Part 1, which was a literature review, confirmed what the previous prognostic studies had indicated, that the practice of staying short of the apex with a homogeneous root canal filling yielded the highest success rate (90–94 %), when done by or under the supervision of a specialist. However, results in the general population resulted in a greater failure rate (>50 %) (Martins et al. 2014). Furthermore, the author indicated that it was impossible to instrument accessory canal ramifications and that, when these ramifications appeared filled on the radiograph, it was only due to the forcing of root canal sealer into the tissues located in these ramifications, which was verified in a later study (Ricucci & Siqueira 2010)… an outcome that was frowned up decades earlier (Grieves 1914a; Grieves 1914b).

In part 2 of the study, Ricucci and Langeland performed histological analysis of teeth that had been root treated and extracted after different observation periods (Ricucci & Langeland 1998). They found that the most favorable histological conditions occurred when instrumentation and obturation remained at or short of the apical constriction, whether the pulp had been vital or necrotic, and even if some bacteria were present in the periapical tissues. Furthermore,

> When the sealer and/or gutta-percha was extruded into the periapical tissues, the lateral canals and the apical ramifications, there was always a severe

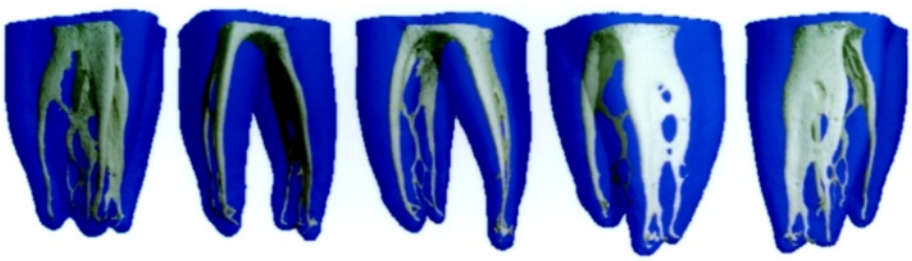

Fig. 16 Micro-CT scans of a mandibular molar from multiple angles that show the highly irregular root canal anatomy from the orifice to the apex (courtesy, Mr. Stephen Rigsby)

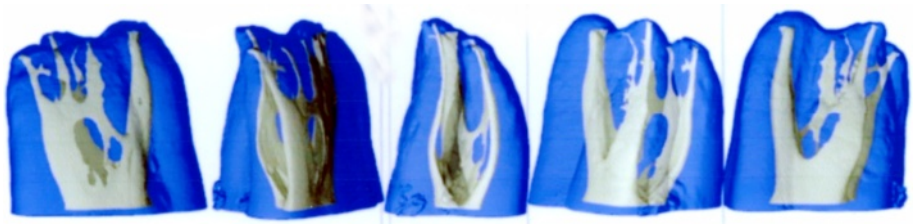

Fig. 17 Micro-CT scans of a maxillary molar from multiple angles that show the highly irregular root canal anatomy from the orifice to the apex (courtesy, Mr. Stephen Rigsby)

> inflammatory reaction including a foreign body reaction despite the absence of pain. (Ricucci & Langeland 1998)

These observations are juxtaposed to those of Khayat (Khayat 2005) and Tamarut et al. (Tamarut et al. 2006), both of which will be discussed below under prognostic studies.

In a unique study that addressed tooth anatomy risk factors that influenced root canal working length accessibility, Tang et al. (Tang et al. 2011) found that tooth type, root canal curvature, canal calcification, and retreatment were primary risk factors in an independent factor analysis. However, using a multiple-factor regression model, root curvature and canal calcification were found to most significantly influence working length accessibility and ultimate treatment success. In particular, as the extent of the canal calcification increased, the difficulty in reaching the root canal constriction increased sevenfold, whereas an increase in canal curvature only increased the difficulty twofold.

Prognostic studies and treatment outcomes

The majority of prognostic studies have been summarized in the publications cited below as to outcomes and dictates, and therefore, these studies do not warrant individual discussion here. Hasselgren in 1994 (Hasselgren 1994), in discussing "Where shall the root filling end?", cited a plethora of studies that every endodontist should be familiar with from 1956 to 1990 that resulted in one finding common to all, and that being, an overfill will markedly decrease the success rate;

> "The optimal result was to end the root filling one to two mm inside the radiographic apex - exactly the same recommendation that emerged from the anatomical studies (in the early 1900s). If the root filling is shorter than that, the success rate will drop; but overfills will yield an even poorer results. (Hasselgren 1994)

Most prognostic studies could only relate to radiographic findings identified at the time of filling and

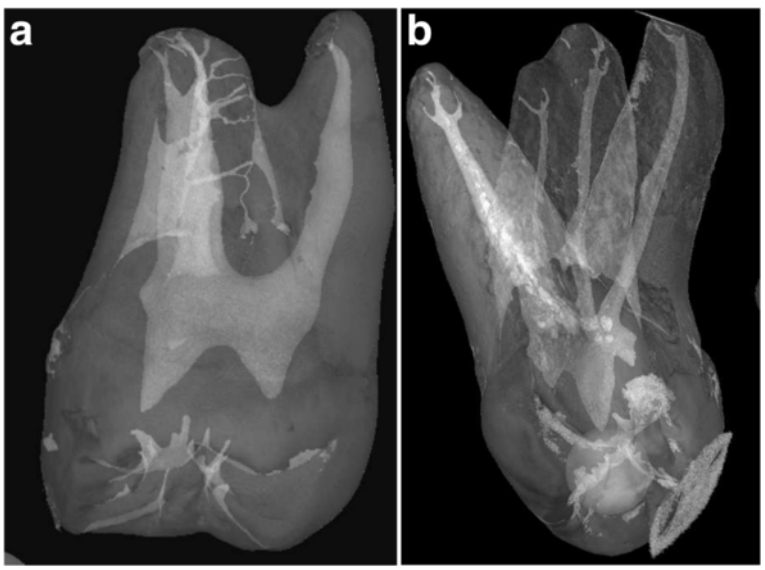

Fig. 18 Micro-CT scan. **a**, **b** Apical termination of the buccal canals on two maxillary molars that show a vast array of canal configurations that make working length determination most difficult (courtesy, Mr. Stephen Rigsby)

Fig. 19 Micro-CT scan. Apical termination of the mesial-buccal root of this maxillary with significant variations in canal termination (courtesy, Mr. Stephen Rigsby)

subsequent control or recall appointments. Therefore, the issue of where the measurement was taken, to what level the canal was "carefully instrumented" and the ultimate obturation, both vertically and laterally may be issues that could never be resolved in the historical studies. Furthermore, outcomes with teeth having vital, inflamed pulps that had obturations that go beyond the confines of the canal may have been worse than teeth with necrotic pulps that had obturations within the canal confines and vice versa depending the degree of canal cleaning and disinfection in each situation. The scenario just addressed brings to the forefront another important issue in these studies, with that being there may be insufficient evidence to support the clinical achievement of bacterial eradication prior to obturation at whatever level the filling is placed. Studies do support better outcomes regardless of the position of enlargement, shaping, and obturation if the root canal is bacteria free. However, two issues come to mind in that regard: (1) that the presence or absence of bacteria at the time of obturation cannot be reliably determined at this point and (2) not every root that contains bacteria at the time of obturation will result in failure, again regardless of the position of the root canal procedures that had been performed (Sjögren et al. 1997). Moreover, and possibly most important, virtually all the studies only used two-dimensional radiographic assessments, which by today's standards may be woefully substandard, as there is substantial disagreements between periapical and CBCT radiographs for assessing the periapical status of molar teeth, especially for the maxillary arch (Cheung et al. 2013). These findings have serious implications in periapical diagnosis and for evaluation of the outcomes of root canal procedures (Cheung et al. 2013).

In 2000, Wu and co-workers did an extensive evaluation of studies over the previous 50 years and arrived at the following conclusion (Wu et al. 2000):

> After vital pulpectomy, the best success rate has been reported when the procedures terminated 2 to 3 mm short of the radiographic apex. With pulpal necrosis, bacteria and their byproducts, as well as infected dentinal debris may remain in the most apical portion of the canal; these irritants may jeopardize apical healing. In these cases, better success was achieved when the procedures terminated at or within 2 mm of the radiographic apex (0 to 2 mm). When the therapeutic procedures were shorter than 2 mm from or past the radiographic apex, the success rate for infected canals was approximately 20% lower than that when the procedures terminated at 0 to 2 mm. Clinical determination of apical canal anatomy is difficult. An apical constriction is often absent. Based on biologic and clinical principles, instrumentation and obturation should not extend beyond the apical foramen. (Wu et al. 2000)

When evaluating the technical aspects of treatment in relation to treatment outcome, Kirkevang and Bindslev arrived at similar conclusions (Kirkevang & Bindslev 2002):

> When the technical quality of the root-filling was related to treatment outcome, the studies demonstrated success rates of 70-100 %, if the quality was assessed to be optimal. If the root-fillings were short of the apex, a lower success rate of 57 %-95 % was found, If extrusion of root-filling material in periapical tissues were found, the success rate was ever lower at 50 %-90 %. (Kirkevang & Bindslev 2002)

Similar findings were identified by Schaeffer and associates in a meta-analysis designed to determine the optimal obturation length (Schaeffer et al. 2005). Very few studies, however, could be considered in this analysis due to inclusion/exclusion criteria. While the data was suggestive and it was considered as biologically sound to obturate short of the radiographic apex, they found that in reality, the length of the fill and success are correlated. Interestingly, they noted that there is opinion held by many clinicians that extrusion of root canal sealer from the root apex (and accessory communications—Author's note) does not lower the prognosis of root canal procedures. While clinically desirable by many to see these puffs or buttons of sealer radiographically, Ricucci and Siquiera (Ricucci & Siqueira 2010) found that

> …vital tissue in the accessory communications was not removed during canal shaping and cleaning and although lateral canals appeared radiographically filled they were actually not obturated, and the remaining tissue in the ramification was inflamed and enmeshed with the filling material. (Ricucci & Siqueira 2010)

This finding supports the dictates of our forefathers, discussed previously, who encouraged the preservation of the tissues in these ramifications to allow normal healing to occur.

In a 10-year clinical follow-up study, a group of investigators from Croatia identified success in comparison to length of root canal instrumentation and obturation in 163 patients (Tamarut et al. 2006). In this study, they used controlled over-instrumentation (1.62 mm ± 0.92 mm) in all pulpal diagnostic states and obturation to the physiological foramen or apical constriction and found that it was not harmful to healing. Furthermore, slight overfilling did not impair success. Keep in mind, radiographic evaluations were done with traditional two-dimensional assessments

In another 10-year follow-up study of 15 single-rooted teeth following root canal procedures from a population of patients aged 25–40, the teeth were extracted due to caries, resorption, or trauma. In order to obtain surrounding apical bone for histological analysis, an apical block dissection was performed (Khayat 2005). While limited in sample size, the teeth had root fillings that were extruded beyond the apex (47 %) or flush with the radiographic apex (53 %). Radiographs showed that 8 of the 15 had overfilling of gutta-percha and sealer, while 7 of the cases had gutta-percha and sealer to the root apex. Healing activity was observed in all cases; however, active macrophage with phagocytic activity was seen even in a case that was 10 years old, which would imply some degree of persistent inflammation. However, many studies of this nature show "healing" in some areas of the periapical tissues, while chronic inflammation can be present in other areas; additionally, healing does not equate with healed (Glossary of Endodontic Terminology 2012).

Most recently, Azim and associates reviewed radiographically 422 roots from 291 root-treated teeth that met an inclusion criteria of a mean follow-up period of 2 years (Azim et al. 2016). Roots instrumented apically within 0.5 mm from the radiographic apex had a significantly more favorable outcome (88 %). Those >2 mm short from the radiographic apex had the least favorable outcome (33 %). Teeth with overextended root fillings showed delayed healing by almost 14 months.

To somewhat mollify the empirical approach to working length determination that was either arbitrarily based on a guesstimate of the apical constriction or on a two-dimensional radiograph, the use of electronic apex locators (EALs) has been favored by most academicians and clinicians (Mohammed et al. 2015). Ironically, the very principles behind the use of the EAL were proffered by Custer in 1918 (Fig. 20) who understood clearly the nature of the canal termination at the root apex (Custer 1918):

> While it is true that the foramen is not always at the extreme apex…there may be more than one foramen to the root, the one method to be presented will meet this condition with precision…an electrical method of extreme delicacy and accuracy…The electrical method is based upon the difference in the electrical conductivity of a dry pulp canal or one filled with a non-conducting liquid, and the conductivity of the tissues just beyond the apical foramen. (Custer 1918)

While popular in its application for working length determination, the EALs have not resolved issues as to the apical limit for canal instrumentation and obturation (Mohammed et al. 2015), as survey results of UK-trained or qualified respondents indicated that the majority preferred to go to the same apical limit with all apical procedures. This is in deference to empirical directives that may indicate that the status of the pulp and periapical tissues may require variations in apical terminations. As

Fig. 20 L. E. Custer—reproduced from Custer LE. Exact methods of locating the apical foramen. J Natl Dent Assoc. 1918;5:815–819

a confirmation of the former choice of relying on the EALs for the working length in all cases, being the same position for all procedures, Tsesis et al. (Tsesis et al. 2015) found the use of the EALs was not influenced by the status of the pulp tissue, although the precision of the length determination was based on the particular device and the type of canal irrigant. In contrast to this issue, Martens and associates, in a systematic review of the literature on the clinical efficacy of the EALs, noted that in addition to using the EALs, and due to the fact that the available scientific evidence base for efficacy is minimal and at risk for bias, at least one radiograph control should be used to detect possible errors in the application and interpretation of data from these devices (Martins et al. 2014).

Empirical directives

There are no guidelines that can be identified with this directive as they are all clinician-based and are determined on a case-by-case basis; however, even this would not be an accurate assessment, as many clinicians manage their apical root canal procedures in the same way for all teeth, that is instrumenting and obturating to the same apical limit (Mohammed et al. 2015), claiming complete success, as long as the patient is comfortable. In this regard, most will follow the dictates of a professor where they received their education or grasp on to the directive given to them in their most recent continuing educational pursuit from those claiming to have the magic way to achieve success. The hallmark of this approach usually is characterized by the presence of root canal sealer puffs and the extrusions of filling materials beyond the root end, with claims of having achieved a perfect seal of the canal system (using only two-dimensional radiographic evaluations).

Status of the dental pulp and periapical tissues

The wide range of anatomical variables and technical interpretations regarding the apical location for determining the working length and the position of the final obturation have been identified. Furthermore, because the actual location of this variable terminal position has resulted in significant number of clinical opinions, along with variable applications and advocacies, at least two camps of polarized thought, along with a vast array of outliers, have evolved. Advocates have been driven by passion, concern for radiographic appearance, staunch adherence to the use of EALs, strong advocacy for patency filing, and the incorporation of cognitive dissonance into their decision-making and proffering (Seltzer & Bender 1965). One major philosophy is to retain all procedures within the confines of the root, while the other philosophy espouses the determination of working length, enlarging, shaping, cleaning, and obturation to the anatomical root apex or root length. In most teeth, while overlap or agreement may occur in some cases, these two philosophies are not compatible. However, in light of this controversy, there seems to be a middle-of-the-road position that most clinicians can travel comfortably and that will yield success. While the choices can vary, it would seem to be dependent on the status of the dental pulp, access to the end of the root, and the clinician's skill and expertise, in addition to experience that demonstrates that particular choices provide positive outcomes in the majority of cases. However, evidence-based data at the highest level to verify this approach are not available, and therefore, it is empirically driven.

If the dental pulp is vital (inflamed; irreversible pulpitis), then the working length is established clinically as close to the constriction as possible and attempts are made to retain all procedures within the root canal. While this position has been advocated as approximately 0.5–1.0 mm from the radiographic apex, this dictate is flawed (Ricucci 1998). In essence, the thought behind this approach is that the tissue that invaginates into the

canal from the periodontal ligament, and which is periodontal in nature, is not disturbed by the subsequent manipulations that are performed within these confines (see Fig. 7) (Gutmann & Reagan 1998; Gutmann 2005). This recommendation is based on sound wound-healing principles in that severance of the tissue at its narrowest point will create the smallest wound possible for healing (Ricucci 1998; Ricucci & Langeland 1998). It also encourages the potential for tissue regeneration with the formation of cementum as opposed to just fibrous connective tissue repair or persistent chronic inflammation (Gutmann 2005).

If the dental pulp is non-vital (obvious necrosis; presence of a periapical radiolucency), then the working length is initially established as close as possible to the canal exit or slightly short of the apical foramen to clean the entire length of the canal (Shabahang et al. 1996), thereby eradicating bacteria as much as possible and removing the substrates that could encourage bacterial regrowth and multiplication (Wesselink & Bergenholtz 2003). This is an empirical and contemporary approach to working length determination, in addition to enlarging and shaping that is promulgated by many in today's practice of endodontics. However, because the root apex can be highly irregular (Fig. 21), especially in the presence of obvious or even unidentified apical resorption (Brynolf 1967), files placed to the apical extent of the root as viewed radiographically will likely be outside the confines of the canal and create potential damage to the root anatomy at that point (Ricucci 1998; Ricucci & Langeland 1998). It is also possible that this technique may serve to inoculate the apical tissues with bacteria and material debris that may cause an adverse reaction or result in persistent inflammation, a concept that was considered as unacceptable by Ottolengui in 1922 (Ottolengui 1922) and highlighted by Yusuf and Love and Firth, when examining biopsies from lesions from teeth that required periapical surgery due to persistent inflammation (Yusuf 1982; Love & Firth 2009). Here also, a middle-of-the-road philosophy has been proposed, that is, cleaning and shaping the canal to the entire length of the root and then backing up or retreating into the canal sufficiently to develop a constriction or stop inside of the root where the dentin terminates for further intracanal procedures (Simon 1994). However, even with this choice, the movement of materials past the root apex into the periapical tissues usually cannot be prevented.

Ironically, both of these philosophical and clinically practiced positions provide no evidenced-based data to support them as the ideal working-length technique for instrumentation and obturation, and it is only when the teeth are obturated can one conjecture where the exact working length was terminated during the procedures. Therefore, data to support either position contemporarily are elusive and unfounded, except for information gleaned from outcome studies that take into account all phases of the root canal procedures. For example, according to Gesi and Bergenholtz (Gesi & Bergenholtz 2003), when no infection is present, it is hard to rationalize, as it is sometimes advocated that the apical foramen be pierced and root canals be overfilled with so

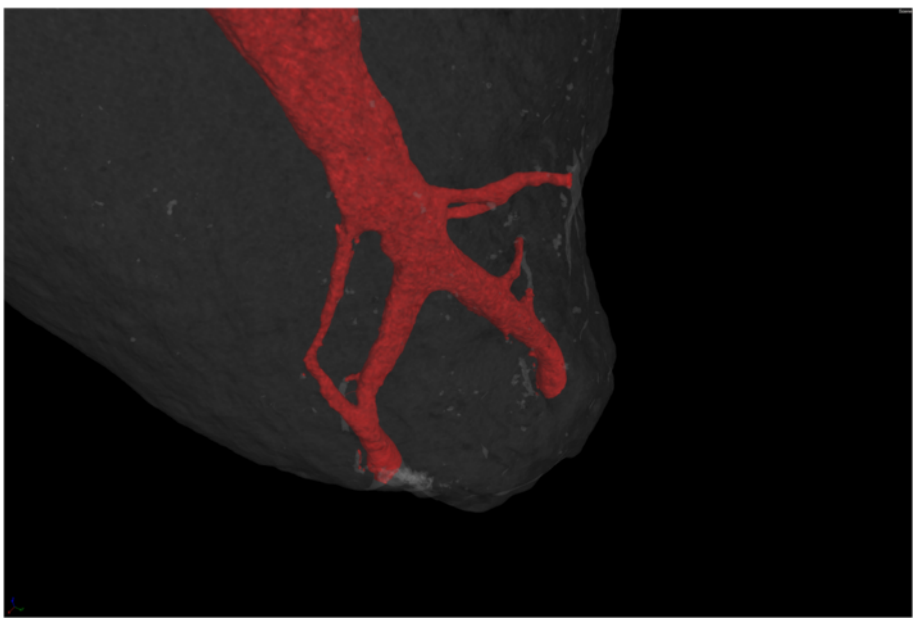

Fig. 21 Micro-CT of the root canal termination showing the anatomical challenges encountered in working length determination (courtesy, Mr. Stephen Rigsby)

called puffs. It would seem that overfills of this nature actually reflect the inexactness of the obturation technique, whereas the clinician is hoping that the canal is truly filled and sealed. Furthermore, an inadvertent overfilling may not necessarily be harmful or cause a periapical lesion to form but may actually reflect a unfavorable apical shaping and alteration of the normal anatomy, which may put the apical tissues at risk for delayed healing or lack thereof (Bergenholtz et al. 1979). Many of these studies that address these issues are retrospective in nature, have questionable bearing on contemporary practices, and are based on two-dimensional radiographic assessment.

Conclusions

In the late 1800s, Cravens warned us that "beyond the apex…danger lurks" (Cravens 1893), while in the early 1900s, Prinz (Fig. 22) made a bold statement regarding the sanctity of the apical constriction: "The hermetic sealing of the foramen without injury to the periapical tissues is the unalterable prerequisite upon which the future welfare of the tooth rests." (Prinz 1928). Finally, following lengthy and thorough assessments of the outcomes relative to the termination of the root canal procedures, in the early 2000s, Gesi and Bergenholtz echoed similar observations: "No scientific basis exists in the literature to support the notion that the apical foramen should be pierced and root canals be overfilled for a successful outcome." (Simon 1994). Is it possible that the lessons of history have gone unheeded or have been obfuscated by contemporary clinical directives, or has empiricism provided total disambiguation in the eyes and minds of the contemporary clinician?

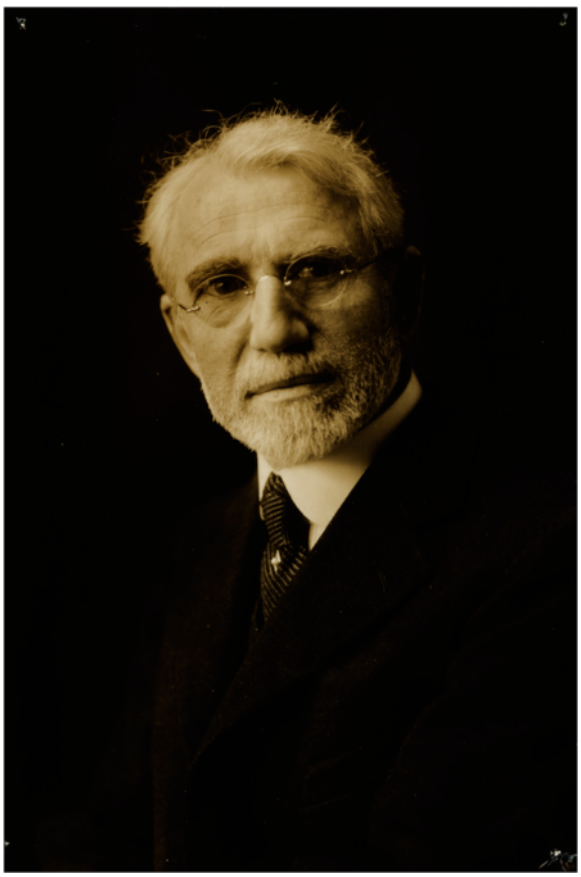

Fig. 22 Dr. Herman Prinz—reproduced with permission from the University Archives and Records Center, University of Pennsylvania, Philadelphia, PA. Also found in Dent Cosmos 1934; 76(1):90

Competing interests
The author declares that he has no competing interests.

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