# The Root Canal Anatomy in Permanent Dentition

Marco A. Versiani
Bettina Basrani
Manoel D. Sousa-Neto
*Editors*

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*Editors*
Marco A. Versiani
University of São Paulo
Ribeirão Preto
Brazil

Bettina Basrani
University of Toronto
Toronto
Canada

Manoel D. Sousa-Neto
University of São Paulo
Ribeirão Preto
Brazil

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*Born in 1452 in the Tuscan village of Vinci, Leonardo was not only a gifted artist but also one of the greatest geniuses who has ever lived. According to him, "practice must always be founded on sound theory, and to this perspective is the guide and the gateway; and without this nothing can be done well." Obviously, this concept can be extended to innumerous human activities, including dental practice. In other words, essential practical and clinical experiences are very important for managing complex cases, but they cannot be a substitute for knowledge and theory. Dentistry was founded in empirical-based research and clinical experience, which means that clinicians often use empirical reasoning to make diagnoses and treatment plans, based on thoughts and follow-up of cases over the years. For several decades, the understanding of the influence of canal anatomy on endodontic procedures was based on empiric observation rather than on rigorous experimentation. Consequently, several authors from the past have stated the impossibility of succeeding in treating infected teeth because of the complexity of the root canal system, which was revealed at the end of the nineteenth century. With the improvement and application of the scientific method in health sciences, however, empirical approach started to be followed by systematic observation, measurement, and experiment. At this point, knowledge of the root and root canal anatomical complexities started to be applied into clinical practice, root canal therapy became more predictable, and endodontics, as a respectful specialty, has born. As the Greek physician Hippocrates postulated that the anatomy is the foundation of medicine, root canal anatomy is undoubtedly the foundation of endodontics!*

*This book is intended for students undergoing specialist training, general practitioner with special interest in endodontics, and specialists alike, being particularly dedicated to the memory of the pioneers in the endodontic field who overcame enormous obstacles to pave the way not only for their own careers or personal wills, but also for giving us inspiration to keep going with their outstanding work and write this book.*

# Foreword I

*Science is the father of knowledge, but opinion breeds ignorance.*

—Hippocrates

Root canal anatomy is the foundation of the art and science of endodontic therapy and succeeding post-treatment healing. Human dentition presents a wide range of anatomical variations in each tooth type. The root and canal morphology is learned to vary greatly between populations, within populations, and even within the same individual. The studies on root canal anatomy from the first half of the nineteenth century highlighted the number of root canals, their configurations, and complexities in teeth, while studies from the second half of the nineteenth century and early twentieth century gained insight on the apical terminus of the root canal anatomy and the periapical tissues that surround it. The knowledge obtained from this cluster of studies formed the bottom line for the biological basis in endodontic treatment. The conception of pulp and periodontal tissue as a continuum, association between endodontic disease and periapical host immune response, as well as the therapeutic significance of apical termination were all emphasized by these studies. Besides, leveraging on the current knowledge, it is recognized that effective nonsurgical root canal treatment and endodontic surgery requires a thorough knowledge of tooth morphology and root canal anatomy. Unfortunately, some of the therapeutic issues associated with complex root morphology and root canal anatomy still remain as challenges.

At the moment it is quite evident that the dental profession needs a broad review of this complex topic—anatomy of the root canal systems and their implications in root canal treatment. Drs. Versiani, Basrani, and Sousa-Neto recognized this requirement and have put together a comprehensive body of knowledge for endodontology. They have compiled some of the finest authorities from around the world to contribute knowledge and insights to this book. The broad list of chapters covered in this book has left no stone unturned. Drs. Versiani and Sousa-Neto as a team have studied root canal anatomy with micro-CT for the last couple of decades. Dr. Sousa-Neto has also used the method of diaphanization since the early 1980s to study root canal anatomy. This team has studied more than 15,000 teeth through these years and published many impactful articles. The experience of this group in this field is obvious from the chapters covered in this book. This book is the most comprehensive overview of root canal anatomy and their clinical implications the dental profession has had the opportunity to review.

There are several reasons for me to be delighted to write the foreword for this book. First, this book represents the maiden attempt to review the root canal anatomy and their related topics using modern high resolution imaging techniques. The dental profession must be updated about this important topic in a structured manner. I am also very pleased because I have known Dr. Versiani for almost 5 years and I am aware of his dedication to endodontology. Dr. Basrani, my colleague at the University of Toronto, was one of the very first internationally trained endodontists to move from Argentina to Canada with great passion for endodontics. This book is a product of their sacrifices, passion, and commitment. I am confident that this book will serve our profession well.

Anil Kishen, B.D.S., M.D.S., Ph.D.
Nanomaterial Guided Functional Tissue Engineering Lab
Dental Research Institute, Faculty of Dentistry
University of Toronto
Toronto, Canada

# Foreword II

The ability to understand and to anticipate root canal anatomy prior to rendering endodontic therapy has remained a challenging issue. Indeed, this issue confronts clinicians every day as they peer into access openings and search for canal orifices. When we read the endodontic literature, we read from time-to-time that a case failed because a second distal canal was overlooked, a third mesial canal was not noticed, a second canal in a lateral incisor was missed, etc. So, what can be done to significantly reduce these oversights?

Dr. Marco Versiani, Dr. Bettina Basrani, and Dr. Manoel Sousa-Neto took up this challenge and engaged tooth anatomy experts from around the world and combined their collective knowledge to prepare a textbook on internal tooth anatomy that should be required reading for every dentist who aims to provide the very finest endodontic therapy. As a reader would expect from a textbook of this caliber, each chapter is enriched with high-quality images and exhaustive citations from peer-reviewed literature.

This textbook is enhanced by also providing online videos and countless photographs derived from some of the most current technologies enabling researchers to even view the complexity of the root canal system in three dimensions. Based on new discoveries, this textbook by Drs. Versiani, Basrani, and Sousa-Neto provides a new nomenclature founded on expanded knowledge that sophisticated technologies have revealed.

Stephen Cohen, M.A., D.D.S., F.I.C.D., F.A.C.D.
Department of Endodontics,
The Arthur A. Dugoni School of Dentistry
University of the Pacific
Stockton, CA, USA

Department of Preventive and Restorative Dental Sciences
School of Dentistry
University of California
San Francisco, CA, USA

Endodontic Postgraduate Program
Riyadh Colleges of Dentistry and Pharmacology
Riyadh, Saudi Arabia

American Board of Endodontics
Chicago, IL, USA

*…superstition and pseudoscience keep getting in the way, […] providing easy answers, dodging sceptical scrutiny, casually pressing our awe buttons and cheapening the experience, making us routine and comfortable practitioners as well as victims of credulity. […] Pseudoscience is easier to contrive than science, because distracting confrontations with reality - where we cannot control the outcome of the comparison - are more readily avoided. […] Pseudoscience speaks to powerful emotional needs that science often leaves unfulfilled. […] Science thrives on errors, cutting them away one by one. False conclusions are drawn all the time, but they are drawn tentatively. Hypotheses are framed so they are capable of being disproved. […] Proprietary feelings are of course offended when a scientific hypothesis is disproved, but such disproofs are recognized as central to the scientific enterprise. […] Science is far from a perfect instrument of knowledge. It's just the best we have.*

Carl Sagan
The Demon-Haunted World: Science as a Candle in the Dark

# Acknowledgments

We would like to acknowledge Springer International Publishing for giving us the opportunity to edit this textbook on root canal anatomy. A special thanks goes to Andrei Berdichewsky, who was responsible for offering us this project.

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To our families, thanks for your encouragement, assistance, and support that allow us to progress in our professional lives.

Marco A. Versiani
Bettina Basrani
Manoel D. Sousa-Neto

# Contents

# Contributors

## Editors

**Marco A. Versiani, D.D.S., M.Sc., Ph.D.** Department of Restorative Dentistry, Dental School of Ribeirão Preto, University of São Paulo, Ribeirão Preto, SP, Brazil

**Bettina Basrani, D.D.S., M.Sc., Ph.D.** Faculty of Dentistry, University of Toronto, Toronto, ON, Canada

**Manoel D. Sousa-Neto, D.D.S., M.Sc., Ph.D.** Department of Restorative Dentistry, Dental School of Ribeirão Preto, University of São Paulo, Ribeirão Preto, SP, Brazil

## Collaborators

**Hany M. A. Ahmed, B.D.S., H.D.D., Ph.D.** Department of Restorative Dentistry, Faculty of Dentistry, University Malaysia, Kuala Lumpur, Malaysia

**Francisco Balandrano, D.D.S.** Private Practice, Torreón, Coahuila, Mexico

**Craig Barrington, D.D.S.** Private Practice in the Waxahachie, Waxahachie, TX, USA

**Christos Boutsioukis, D.D.S., M.Sc., Ph.D.** Department of Endodontology, Academic Centre for Dentistry Amsterdam (ACTA), University of Amsterdam and Vrije Universiteit Amsterdam, Amsterdam, The Netherlands

**Clóvis Monteiro Bramante, D.D.S., M.Sc., Ph.D.** Dental School of Bauru, University of São Paulo, Bauru, Brazil

**Arnaldo Castellucci, M.D., D.D.S.** Private Practice Limited to Endodontics, Florence, Italy

University of Cagliari Dental School, University of Naples, Federico II

**Antonis Chaniotis, D.D.S., M.Sc.** Department of Endodontics, Athens Dental School, University of Athens, Athens, Greece

University of Warwick, Coventry, UK

Private Practice Limited to Endodontics, Kalithea, Greece

**Gustavo De-Deus, D.D.S., M.Sc., Ph.D.** School of Dentistry, Fluminense Federal University, Niterói, RJ, Brazil

**Paul M. H. Dummer, D.D.S.c., M.Sc., Ph.D.** School of Dentistry, College of Biomedical and Life Sciences, Cardiff University, Cardiff, UK

**Diogo Guerreiro, D.D.S., M.S.** Resident ASE Endodontics, School of Dentistry, University of Michigan, Ann Arbor, MI, USA

**James L. Gutmann, D.D.S., Ph.D., F.I.C.D.** Texas A&M University College of Dentistry, Dallas, TX, USA

**Jojo Kottoor, B.D.S., M.D.S.** Department of Conservative Dentistry and Endodontics, Indira Gandhi Institute of Dental Sciences, Ernakulam, India

**Jorge N. R. Martins, D.D.S., M.Sc.** Dental School of Lisbon, University of Lisbon, Lisbon, Portugal

**Carlos Murgel, D.D.S., M.Sc., Ph.D.** Private Practice Limited to Endodontics, Campinas, Brazil

**Sergiu Nicola, D.D.S.** Private Practice, Bucharest, Romania

**Ronald Ordinola-Zapata, D.D.S., M.Sc., Ph.D.** Dental School of Bauru, University of São Paulo, Bauru, Brazil

Bender Division of Endodontics, Albert Einstein Medical Center, Philadelphia, PA, USA

**Elizeu A. Pascon, D.D.S., M.Sc., Ph.D.** Private Practice, São Paulo, SP, Brazil

**Jesus D. Pécora, D.D.S., M.Sc., Ph.D.** Department of Restorative Dentistry, Dental School of Ribeirão Preto, University of São Paulo, Ribeirão Preto, SP, Brazil

**Mário R. Pereira, D.D.S., M.S.** Department of Endodontics, University of Lisbon, Lisbon, Portugal

Department of Endodontics, ISCSEM, Lisbon, Portugal

**Nicola Perrini, M.D., D.D.S.** Private Practice in the Centro di Odontoiatria e Stomatologia at Pistoia, Pistoia, Italy

**Nuno Pinto, D.D.S., M.Sc.** Private Practice in the Mayo Clinic at Lisbon, Lisbon, Portugal

**Domenico Ricucci, M.D., D.D.S.** Private Practice, Cetraro, Italy

**Isabela N. Rôças, D.D.S., M.Sc., Ph.D.** Molecular Microbiology Laboratory, Faculty of Dentistry, Estácio de Sá University, Rio de Janeiro, RJ, Brazil

**José F. Siqueira Jr., D.D.S., M.Sc., Ph.D.** Department of Endodontics, Faculty of Dentistry, Estácio de Sá University, Rio de Janeiro, RJ, Brazil

**Hugo Sousa, D.D.S., M.Sc.** Clinical Residency, Foramen Dental Education, Porto, Portugal

Private Practice Limited to Endodontics, Porto, Portugal

**Oscar von Stetten** Private Practice, Stuttgart, Germany

**Leo Tjäderhane, D.D.S., Ph.D.** Department of Oral and Maxillofacial Diseases, University of Helsinki, Helsinki, Finland

Institute of Dentistry, University of Oulu, Oulu, Finland

Helsinki University Hospital, Helsinki, Finland

Research Unit of Oral Health Sciences, and Medical Research Center Oulu (MRC Oulu), Oulu University Hospital and University of Oulu, Oulu, Finland

# Part I

# Fundamentals of Root Canal Anatomy

# 1 Historical Overview of the Studies on Root Canal Anatomy

Nicola Perrini and Marco A. Versiani

**Abstract**

The fundamental basis of the endodontic specialty is the knowledge of root canal anatomy. Thus, a thorough understanding of the canal morphology and its variations in all groups of teeth is a basic requirement to improve the outcome of the endodontic therapy. In the past, a lot of research work was done on this subject, and the findings have had a noteworthy influence on clinical practice as well as on dental education. Therefore, it would be appropriate to take a brief look to the past to understand contemporary research approaches on the study of root canal anatomy. Authors that preceded this new image-processing technological era, to whom endodontics are greatly indebted, must be revisited.

## 1.1 Introduction

From the Latin *anatomia*, dissection, and from the Greek *anatome*, where *ana* means "up" and *temnein* means "to cut," this word represents the study of the body, the determination of the regions in an organism that are to be considered its parts. Writing about the historical aspects of the studies on root canal anatomy does not simply mean to place the stages that lead to the current knowledge chronologically or compiling the biography of the authors. In fact, the history of endodontic as a dental specialty is relatively recent and was born with the better understanding of the morphology and biology of teeth, as well as the development of endodontic techniques in the brief period of 30 years, from 1900 to 1930, after centuries of immobility [1]. Consequently, this historical overview was carried out considering the result of a long cultural and scientific evolution that simultaneously influenced medicine and its other biological branches, including dentistry.

## 1.2 From Classical Antiquity to Thirteenth Century

The ancient Greek anatomist *Herophilus* (c.335–c.280 B.C.), founder of the school of anatomy of Alexandria, and his disciple *Erasistratus* (c.310–c.250 B.C.) were the first physicians to perform systematic dissection of human bodies. *Herophilus* has been widely acknowledged as the "father of anatomy" and hailed as one of the greatest anatomists that ever lived. His revolutionary discoveries represented an important step in the ancient understanding of the human anatomy [2]. Some

N. Perrini, M.D., D.D.S. (✉)
Private Practice in the Centro di Odontoiatria e Stomatologia at Pistoia, Pistoia, Italy
e-mail: n.perrini@cioesse.it

M. A. Versiani, D.D.S., M.Sc., Ph.D.
Department of Restorative Dentistry, Dental School of Ribeirão Preto, University of São Paulo, Ribeirão Preto, SP, Brazil


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centuries later, the works of *Claudius Galenus* (c.130–c.210 A.C.), usually known as *Galen*, have influenced several generations of physicians and the development of various scientific disciplines, including anatomy [3]. In his writings, *Galen* did not just content to compile antique data but also to observe and experience [1].

From the time of Galen's death until Renaissance, there was no substantial progress in the understanding of human anatomy. In the Middle Ages, the anatomical drawings of human beings were completely devoid of realism, and anatomical description of the teeth was limited to their quantity, position in the oral cavity, and number of roots [1]. Physicians suffered greatly from stasis and intellectual stagnation, once medical knowledge was limited to glossaries, commentaries, encyclopedias, and compendia of ancient works from Arabic writers such as *Avicenna* [4], *Rhazes* [5] and *Albucasis* [6]. In the anatomical field, the influence of Galen's writings continued to prevail.

## 1.3 From Fourteenth to the Seventeenth Century

The Renaissance, period that immediately followed the High Middle Ages (eleventh to thirteenth century) in Europe, was the turning point in which natural sciences and medicine were under the general principle of critical revisionism. At the end of the fourteenth century, medical science slowly found noteworthy progress because dissections became an accepted and officially recognized procedure in Bologna, Italy. This allowed *Mondino de Liucci* (1270–1326) to write his book *Anathomia Corporis Humani* [7], possibly the first work exclusively devoted to anatomy. This 83-page book left a profound intellectual legacy and renewed the way to understand and teach human anatomy through direct observation of dissected corpses. *Mondino* dedicated four pages to the anatomy of the mouth and wrote about the number and function of teeth, but nothing related to their internal anatomy [1]. In 1363, *Guy de Chauliac* performed the greatest synthesis of medical and surgical knowledge of his time by writing the famous book *Chirurgia Magna* [8]. Again, however, description of teeth's anatomy and physiology was presented superficially [1].

At the end of fifteenth century, the realism demanded by the aesthetic of the art in the Renaissance age led various artists to undertake in-depth studies of the human anatomy directly on corpses, or indirectly by attending university classes of anatomy, to elaborate artistic compositions proportional to structures and shapes of the human body. Circa 1510 *Leonardo da Vinci* (1452–1519), working on human anatomy in collaboration with *Marcantonio della Torre* (1478–1511), a renowned anatomist, compiled a series of sheets with more than 240 individual drawings and over 13,000 words of notes, in a work that is considered one of the most significant achievements of Renaissance science [9]. Among these drawings, *Leonardo* accurately depicted the maxillary and frontal sinuses, the curvature of the dental arches in centered occlusion, and the external morphology of four teeth. It is interesting to notice, however, that even with the innovations of the anatomical studies with cadavers, morphological description of the dental organs in this period was practically ignored, not to mention the internal anatomy that, according to *Galen*'s dictates, did not exist [1].

In the first half of the sixteenth century, a set of seven books written by *Andreas Vesalius* (1514–1564) entitled *De Humani Corporis Fabrica* were published [10]. This was the major advance in the history of anatomy over the long-dominant works of *Galen* and *Mondino* and has been recognized as the first complete treatise on human body. Unlike *Leonardo da Vinci*, *Vesalius* had a fruitful collaboration with the outstanding painter *Jan Steven van Calcar* (1499–1546), responsible for the anatomical plates conceived for the book. Despite the anatomy of the teeth was not treated so deeply as the other parts of the body, description of the dental apparatus was considerably more accurate than that of *Galen* and represented a real progress in the morphological knowledge of the mouth and teeth. It is noteworthy that an important anatomical aspect of teeth that had been ignored by previous authors, on which, centuries later, the

endodontic specialty would be born, was highlighted for the first time in the literature. In Chap. XI, there is the first registered drawing of a sectioned two-rooted mandibular molar showing its internal anatomy: the pulp chamber and two root canals [1]. In 1563, *Bartolomeo Eustachi* (c.1520–1574), in his treatise *il Libellus de dentibus*, made very significant contributions toward the anatomy and physiology of the dentition, including the first descriptions of the dental pulp, the periodontal membrane, the dental follicles, the trigeminal nerve, and other oral structures, based upon extensive dissections of both human and animal material [11]. In Chap. XVIII, *Eustachi* speaks about the pulp cavity and its content, and shows accurate tables in which he specified the number of roots and the external morphological variations of all groups of teeth. Eustachi's book brought the macroscopic anatomy of teeth to a high degree of perfection that remained unsurpassed until the nineteenth century [1].

In the seventeenth century, the first sign of separation between oral sciences and medicine emerged with the publication of several works dedicated to the dental field, despite most of the schematic images had been copied from *Vesalius*' book. In 1675, *Antonie van Leeuwenhoek* (1632–1723), using a compound microscope created by himself, was the first author to describe the microscopic anatomy of the dentinal tubules. It led him to disagree with the predominant concept according to which teeth were like bone structures. He also published drawings of a sectioned mandibular molar showing its pulp chamber and the root canals [12]. *Marcello Malpighi* (1628–1694) was also one of the greatest microscopist of this century. In his manuscript *Observationes de dentibus*, there are 27 sheets richly depicted by drawings of sectioned and non-sectioned human teeth in different angles [13], some of which published in the posthumous edition of his *Opera Medica, et anatomica varia* [14], that remained unpublished until 1968 [15–17]. Undoubtedly, the works of *Leeuwenhoek* and *Malpighi* were too advanced for their time and lacked adequate practical application. Therefore, they remained neglected for at least another 150 years.

## 1.4 From the Eighteenth to the Nineteenth Century

In 1728, the French dentist *Pierre Fauchard* (1678–1761), also known as the "father of modern dentistry," published the first edition of his two-volume treatise entitled *Le Chirurgien Dentiste ou Traité des dents* [18], universally acknowledged as the first scientific work of conservative, surgical, and prosthetic dentistry that reflected the state of the art of dental care at that time. However, despite the external morphology of teeth had been described in detail, no information was provided about the root canal anatomy. At the end of the eighteenth century, *John Hunter* (1728–1793) published two important books based on more than 15 years of observation and experimentation on human dentition [19, 20]. In his former treatise, *Hunter* performed a complete and original analysis of the human dentition that had never been made. Regarding the canal anatomy, the available images are not numerous, but show root canal changes with aging. In summary, several works dedicated to teeth were published in this century, but new anatomical knowledge of teeth was scarce and remained unchanged since the sixteenth century.

The nineteenth century witnessed the rise of dentistry as a distinct profession, with its own practitioners, techniques, standards, and specific literature devoted to dental science [1]. But in the first half of the century, only a few authors have published new anatomical aspects regarding the root canal morphology. *Meyerus Fraenkel*, a student of the great anatomist *Jan Evangelista Purkinje* (1787–1869), can be considered a precursor of the modern studies on root canal anatomy because, in his thesis [21], there are some drawings in which horizontal sections in different root levels of a single-rooted incisor and a double-rooted premolar are shown. Some years later, *Georg Carabelli* (1787–1842), in his posthumous work [22], provided the most detailed description of the number and direction of the root canal until that moment. Unfortunately, these remarkable studies, undeniably modern in their conception, were completely disregarded and considered unworthy of interest [1].

In the second half of the nineteenth century, dentistry was overwhelming by the great paradox created between the microscopic and macroscopic studies. While the former had already characterized the tooth structure, the latter had not yet defined the morphology of the root canal system. In 1870 in Germany, *Eduard Mühlreiter* (1839–1917) published the first complete study on the root canal anatomy of human teeth in which the external and internal morphologies of teeth were compared through sagittal and horizontal sections [23]. Even though it was a simple work in its essence, it proved to be extremely important because it served as inspiration to other researchers, such as *Adolph Witzel* (1847–1906), to study the root canal anatomy. This author showed, for the first time, the anatomical variability of root canal system in maxillary premolars and the morphological changes of the pulp cavity of mandibular molars with aging [24]. In the United States, *Greene Vardiman Black* (1836–1915) examined the external and internal morphology using images of sagittal and horizontal sections of each group of teeth [25]. A few years later, *Alfred Gysi* (1865–1957), using histological sections, published the first high-quality photomicrographs depicting the internal morphology of a carious molar and the pulp-dentin complex of another molar, in which it is possible to observe details of the soft connective tissue such as the vascular, lymphatic, and nervous elements [26].

Nevertheless, it was only at the end of nineteenth century that some researchers finally realized the need for an in-depth research on the root canal morphology. It happened mostly because of the rise of misconceptions about root canal infection. At that time, *Willoughby Dayton Miller* (1853–1907) proposed that oral microorganisms or their products have a role in the development of a variety of diseases in other parts of the body, such as brain abscesses, pulmonary diseases, and gastric problems [27]. Although *Miller* advocated treating the root canals to eliminate the focus of infection, teeth extraction was popularized at the turn of the century because of further reports from *William Hunter* [28, 29] and *Frank Billings* [30, 31], which started the era of focal infection theory. These evidences led many researchers to consider that the main cause of root canal treatment failure was the lack of knowledge regarding the internal morphology of teeth [32, 33].

## 1.5 From Twentieth to Twenty-First Century

In 1903, *Gustav Preiswerk* (1866–1908) performed a profound and comprehensive research on the root canal anatomy. In his pioneering study [34], Wood's metal, an alloy that melts at a low temperature, was molten and injected into the canal space. After complete decalcification of the teeth, three-dimensional metal models of the internal anatomy were obtained. It is important to point out that this method was developed by the Dutch anatomist *Govard Bidloo* (1649–1713) using melted bismuth [35], later improved by *Brunn*, who employed Wood's metal, and used by *Zuckerkandl* in the study of pulp chamber [1]. This method, however, led to tooth overheating and the replicas were obviously incomplete, as the metal could not penetrate into the finer branches of the root canal system. Despite these methodological drawbacks, this innovative method allowed *Preiswerk* [34] to observe that canal anastomosis was not rare. Since then, the classical descriptions of teeth with regular canal anatomy and a single apical foramen that appeared in almost all previous treatises started to be questioned.

*Guido Fischer* (1877–1959) presented the challenging nature of the apical root anatomy for the first time in 1907 [36]. He obtained better results than *Preiswerk* [34] by filling approximately 700 teeth with a collodion solution. This solution could penetrate all the branches of the root canal system and hardened in 2 or 3 weeks, providing a full three-dimensional replica of the canal. But the hardened collodion solution was fragile, and replicas of the subtler ramifications fractured easily. *Fischer* paid special attention to thin ramifications, little lateral branches, and apical terminations and classified the morphological variations of the root canal into simple ramifications or branches, lateral canals within the radicular dentin, intercommunicating canal

system, and islands of hard tissue within the canal. The complexity and unpredictability of the root canal morphology led him to coin the nowadays widely used term "root canal system" (*Kanalsystem*). In the next 2 years, *Fisher* started to associate radiography [37] with his macroscopic and microscopic observations [38], highlighting the morphological complexity of the root canal system. It may be said that the innovative three-dimensional anatomical studies of *Preiswerk* and *Fisher* resulted in huge advancement adding new and significant knowledge to dental literature, which stimulated other researchers to undertake further investigations on the anatomy of the root canal system.

In 1911, the German anatomist *Werner Spalteholz* (1861–1940) developed a process by which organs could be made translucent and stained using assorted colors [39]. This process was based on dehydration of the removed organs and the use of an optically transparent embedding material that has the same refractive index as the tissue of the organ itself. At this same year, in Japan, *T. Okumura* used numerous grinding sections to investigate the relation between the external and internal structure of the teeth [40]. He measured several important root canal parameters including the position of the pulp chamber floor, the thickness of the dentinal wall, the distance from the cervical line to the furcation area, and the number, size, and shape of apical ramifications. However, this study was published in Japanese and, therefore, did not have the expected international recognition. In 1913, Spalteholz's method [39] was used for the first time by Fasoli and Arlotta, from the University of Milan, in Italy, to study the root canal anatomy [41]. In the next years, this technique was modified and employed for the study of the internal anatomy by injecting fluid materials into the root canal system [42, 43]. Since then, it has been referred to as "clearing" or "diaphanization" technique.

In 1914, *H. Moral* reported another method in which hard tissues were made transparent and pulp cavity was filled with Indian ink [44]. Using this approach, the author demonstrated, among other findings, that the percentage frequency of a fourth root canal in the mesiobuccal roots of 100 maxillary molars was 63% [45]. A few years later, *Walter Hess* (1885–1980) published noteworthy results on the root canal anatomy from a sample comprising 2800 permanent human teeth [46]. He succeeded in reconstructing the root canal shape on such a large scale by using a novel approach that involved filling the teeth with vulcanized rubber followed by decalcification. *Hess* complemented his findings by carrying out grinding sections of selected teeth to illustrate the fine structures of the root canal system at the apical region, establishing a correlation between the frequency of ramifications and the patient's age, which confirmed Fischer's findings. This study was followed by a second one conducted by *Ernst Zürcher*, in 1922, under his supervision [47]. These are undoubtedly the most important and detailed studies on root canal anatomy, which were later joined together and published in English language [48]. In the following years, the results obtained by the German school regarding root canal [34, 36, 46] were finally confirmed by several authors from different countries [49–53].

*Wallace Clyde Davis* (1866–1950) was the first author to detail the internal morphology of the root canal at the apical third and to address the problem regarding the inability to remove all pulp tissue from the root canal system. He prepared and photographed, at 25× magnification, 50 sectioning root apexes of different teeth from patients ranging from 25 to 45 years old [54]. *Davis* also introduced the terms *pulpotomy* and *pulpectomy* in dentistry. With the publication of his book in 1920 [55], he contributed to the endodontic knowledge of future dentists by favoring the development of non-empirical training techniques with scientific foundations. In 1926, *T. Okumura* showed, at the 16th International Dental Congress of Philadelphia, the results of his study using the Spalteholz' method on the root canal anatomy of 2146 teeth. Okumura's work is undoubtedly the most important anatomical study of the root canal system using diaphanization method because of the large sample and the conclusions reached. As an unfolding of his work, he categorized the canal anatomy into four types, according to the root shape, the divisions of the main root canal, and the presence of ramifica-

tions, being considered the first anatomical-based classification of the root canal system. In 1928, the third and last work under *Hess* supervision was performed by *Oskar Keller* using 960 teeth [56], synthesizing all knowledge on root canal morphology since *Preiswerk* [34]. In this study, a new method combined the *Spalteholz* technique [39] with modifications [12, 41] and was virtually free of artifacts and suitable for highlighting even the smallest branches of the root canal system. Based on the three studies of *Hess*, in which the internal anatomy of almost 5000 teeth was studied, root canals ceased to be only "a complex structure" to become a well-defined structure in which scientific-based treatments could be developed and applied [1].

In addition to the invasive techniques, X-ray imaging was soon found to constitute a valuable approach to understand variations in the internal structure of the human tooth. Using this method, *Augustus Henry Mueller* [57] investigated extracted teeth filled with gutta-percha. It is important to point out that, at this same period in the Latin American, *Pucci* and *Reig* [58] also performed an extensive study on root canal anatomy using radiography, diaphanization, and sectioning techniques. However, most of the in-depth research studies on canal anatomy conducted by them was not published in English, which avoided this knowledge to be spread throughout the world. In the years that followed, the advent of the Second World War affected most of the oral research centers around the world. As a consequence, several authors kept reproducing in their books the canal anatomy as previously reported by *Mühlreiter* [1].

After the war, *Balint W. Hermann*, known for introducing the calcium hydroxide in dentistry in 1920, published some images reproducing the complexity of the root canal morphology at the apical region [59]. Some years later, *David Green* also studied the apical anatomy of all groups of teeth using stereomicroscopy [60–62]. In a series of anatomical studies, *Wilhelm Meyer* reported a new protocol to reproduce three dimensionally the internal anatomy of 800 teeth based on drawings of sequential microscopic sections of the root canal systems [63–67]. *Quintiliano de Deus* was the first author in Brazil who studied systematically the root canal anatomy of all teeth using diaphanization technique. He also evaluated the percentage frequency of lateral canals in each dental group [68]. Later, *Vertucci and colleagues* [69–74] made a significant step forward documenting a broad morphological variation in the root canals of different teeth using clearing technique, which became a standard method in further reports on root canal anatomy [75–82]. These works closed the series of major studies on root canal morphology, accomplishing the results of *Preiswerk* [34], *Fisher* [36], *Hess* [48], and others.

In the twentieth century, technological advancements allowed that a considerable range of other techniques was also successfully employed to visualize the anatomy of human teeth including three-dimensional wax models [65], digital radiography [83], resin injection [84], radiographic methods with radiopaque contrast media [85], scanning electron microscopy [86], and others. Undoubtedly, these techniques have shown a great potential for endodontic research; however, while most of these methods required the partial or even full destruction of the studied samples, rendering irreversible changes in the specimens and many artifacts, others provided only a two-dimensional image of a three-dimensional structure [87]. These inherent limitations have repeatedly been discussed in the literature, encouraging the search for new methods with improved possibilities [88].

In 1986, *Mayo and colleagues* [89] introduced computer-assisted imaging in the field of endodontic research by injecting contrast medium into the root canal and taking six radiographs of each tooth from known angles. By combining all six views, a mathematically determined three-dimensional (3D) representation of the canals was obtained. From this data, the volume and diameters of the root canals were determined using a computerized video image-processing program. This radiographic volume interpolation method was also used in further studies to evaluate the root canal anatomy [90–92]. The early to mid-1990s, the first application of a computerized and digital approach based on micrographs of grinding sections was

proposed. Using diamond and silicon carbide disks, *Blašković-Šubat* et al. [93] and *Lyroudia* et al. [94, 95] cross-sectioned extracted teeth and photographed these sections using a camera attached to a stereomicroscope. Each photograph was then digitized, the shape was manually outlined, and the resulting stacks of labeled shapes were rendered in 3D using dedicated software. Although partly digital, this approach still required the destruction of the samples under study [96].

The invention of X-ray computed tomography (CT) brought a significant step forward in diagnostic medicine [97]. CT produces a two-dimensional map of X-ray absorption into a two-dimensional slice of the subject. This is achieved by taking a series of X-ray projections through the slice at various angles around an axis perpendicular to the slice. From this set of projections, the X-ray absorption map is computed. By taking a number of slices, a three-dimensional map is produced [98]. To maximize their effectiveness in differentiating tissues while minimizing patient exposure, medical CT systems need to use a limited dose of relatively low-energy X-rays (≤125 keV) and acquire data rapidly because the patient should not move during scanning. Besides, to obtain as much data as possible given these requirements, CT devices use relatively large (mm scale) and high-efficiency detectors [99].

In 1990, *Tachibana and Matsumoto* [100] were the first authors to suggest and evaluate the feasibility of CT imaging in endodontics. Because of high costs, inadequate software, and a low spatial resolution (0.6 mm), they concluded that CT had only a limited usefulness in endodontics as the acquired images were not accurate for detailed analysis. Further improvements in digital image systems have been used to evaluate the root canal anatomy in either *ex vivo* or *in vivo* conditions using nondestructive tools such as conventional medical CT [101], magnetic resonance microscopy [102], tuned-aperture computed tomography (TACT) [103], optical coherence tomography [104], and volumetric or cone beam CT (CBCT) [105]. However, these digital image systems were hampered mainly by insufficient spatial resolution and slice thickness for the study of root canal anatomy [106, 107].

A decade after the CT scanner was created, *Elliott and Dover* [108] developed the first high-resolution X-ray micro-computed tomographic device, and, using a resolution of 12 μm, the image of the shell of a *Biomphalaria glabrata* snail was produced. The term "micro" in this new device was used to indicate that the pixel sizes of the cross sections were in the micrometer range. This also means that the machine was smaller in design compared to the human version and was indicated to model smaller objects [109]. More recently, micro-CT has gained increasing popularity in endodontics. This noninvasive, nondestructive, high-resolution technology allows three-dimensional study of the root canal system by reconstructing digital cross sections of the teeth, which can be stacked to create 3D volumes. These volumes can be used to generate computerized images of specimens that can be manipulated, sectioned, prepared, dissected, and measured to reveal both internal and external morphology [110]. In endodontics, *Nielsen et al.* [107] was the first authors to apply micro-CT technology to reconstruct the external and internal anatomy of four maxillary molars. Then, *Dowker* et al. [106] and *Bjørndal* et al. [111] used micro-CT to demonstrate root canal anatomy and the feasibility of using this methodological resource in different stages of the root canal treatment. Nowadays, despite the impossibility of employing micro-CT for *in vivo* human imaging, it has been considered the most important and accurate research tool for the study of root canal anatomy [87, 112–114].

As previously outlined, it is very important for the clinician to develop a complete understanding of the 3D morphologic features of root canal systems. The morphological studies of the last centuries gave us a better understanding of the internal anatomy of teeth (Figs. 1.1, 1.2, and 1.3) and allowed the development of technological resources aiming to overcome the treatment limitations imposed by the anatomical complexities of the root canal. From the present century, it may be expected that this accumulated knowledge provides improvements in the endodontic

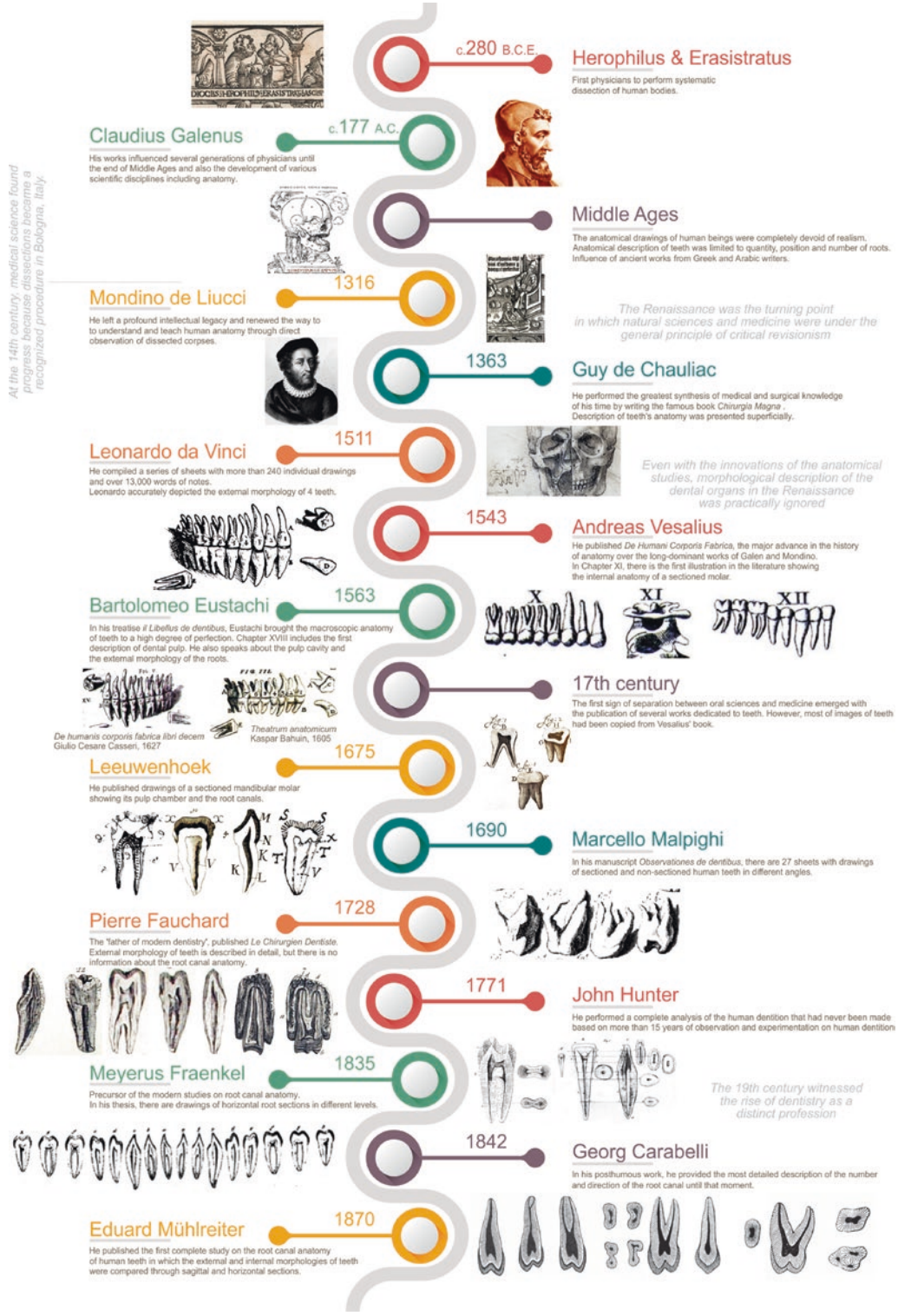


**Fig. 1.1** Timeline infographic of the studies on root canal anatomy (from classical antiquity to 1870) (images reproduced from Perrini [1] with permission)