9 Pulp Inflammation: From the Reversible Pulpitis to Pulp Necrosis During Caries Progression

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9.1 Setting the Stage

This chapter aims to present an overview of the pulpal events taking place in relation to caries progression and in different stages of lesion activity, from the very first cellular pulp reactions to the non-cavitated enamel caries toward progressive stages of pulpal inflammation including necrosis. Where is the border between a beneficial/reversible inflammation as opposed to unwanted/irreversible inflammation? The former is a prerequisite of repair, from which treatment can be successfully carried out with or without exposure of the pulp, whereas the latter leads to apoptosis and necrosis, and, if left untreated, to further bacterial invasion in the pulp cavity.

To improve the connection between the science of pulp biology in the laboratory and actual clinical treatment concepts, it is important to maintain a link between the visible signs of disease at both a macroscopic and histological level of examination. For example, what do caries look like in progressive stages of caries lesion formation? For obvious reasons, it is not possible to repeat histological data from the same carious lesion over time. Therefore, when progressive cellular events are described, it must be based on different carious lesions in progressive stages of lesion development.

In previous papers [1, 2] and textbooks [3–5], it has been stated that the signs and symptoms do not allow to consistently diagnose the histological status of the pulp and consequently the reversibility or irreversibility of pulp inflammation. However, is it possible to clarify at what lesion stages these problems of interpreting do most often occur? In this chapter we will specify the lesions by using information on progression stage, lesion activity and estimated length of progression time (patient age), including recent clinical evidence from treatment of deep caries lesions. Finally, from a histological viewpoint, it is clear that the point of no return for unwanted inflammation in the pulp can be defined and will be clarified in this chapter because confusion exists among clinicians and researchers.

9.2 The Dilemma of the Difference Between Histology and Clinical Pulp Diagnosis

Although the pulp is the vital tissue connecting the tooth with the body, it constitutes an entity that in the clinical setting is very difficult to monitor in terms of stage of inflammation. No device

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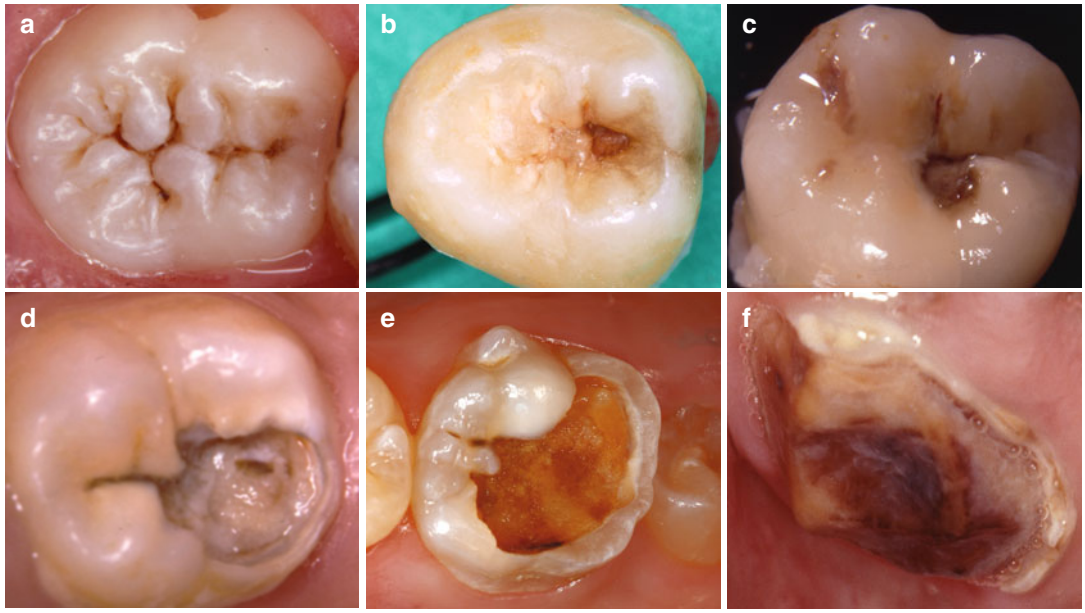

Fig. 9.1 Macroscopical views of progressive stages of caries in different molars. (**a**) Occlusal lesion without clinical dentine exposure in mandibular molar. (**b**) Occlusal lesion with initial dentine exposure reflecting a closed lesion environment in a mandibular molar. (**c**) Occlusal lesion with established dentine exposure. Note that the undermined enamel is reflected as change in enamel translucency surrounding the clinical cavity, also described as retrograde demineralization along the enamel-dentine junction. A macroscopical cutting plane of this lesion is shown in Fig. 9.2b. (**d**) A gradual breakdown is taking place in a mandibular molar; note the milky appearance of the cavity border reflecting the retrograde demineralization. (**e**) In principal, a more advanced stage of enamel breakdown from a maxillary molar. The ecosystem has started to become more open, and the change in microbial growth condition is clearly reflected by a less pronounced biofilm. (**f**) The occlusal enamel here is completely broken away and a "new" occlusal dentine surface has emerged. The clinical appearance of the carious dentine is dark at the central area. This case represent a clinical example of an open lesion environment, with a temporarily arrest at the occlusal site, whereas along the peripheral borders the cariogenic biofilm is clearly present, maintaining a high lesion activity. The case reflects the relative importance of a marked change within a local ecosystem

is available for a noninvasive estimation of pulp inflammation in a routine clinical setting [5, 6], for providing an objective answer to whether the pulp can be saved or not during treatment of deep caries approximating to the pulp. Therefore, the clinicians are forced to apply indirect methods for their clinical diagnoses [7, 8]. Consequently, it is important to underline that when the clinical diagnoses are suggested such as *pulpitis irreversibilis* or *pulpitis reversibilis*, they are *not* based on a true histopathological platform.

Previous histological studies have not always specified the clinical data about the origin of the teeth, age of patients, as well as information about the specific lesion environment being active or arrested [1, 2]. This chapter attempts to present the conditions of the pulp based on different carious lesions in progressive stages of lesion development (Fig. 9.1a–f). This is not optimal as the history of the natural caries lesion may vary, but it will indicate in which lesion types the dilemma of pulp inflammation occurs.

The diagnosis of the condition of the pulp has been systematically reviewed [6] and with only a few papers, accepted for inclusion. Of these, the scientific level of evidence was most often low due to methodological shortcomings. However, the following features were found:

- No obvious association between cold, heat, electric pulp test, and percussion in deep asymptomatic caries and status of pulp inflammation [9].

- Irrespective of the degree of inflammation, the majority of patients may respond to a percussion test, even though the teeth have minimal or no pulp inflammation.
- It is important to stress the unreliability of pain as a parameter for the clinical assessment of reversibility/irreversibility of pulpal inflammation. Severe inflammatory reactions can be observed in teeth with no history of pain.
- Despite the presence of spontaneous pain, indicative of irreversible pulp inflammation, histologically it is possible to find no evidence of pulp exposure or necrosis in the pulp tissue, indicating that the point of irreversibility had not been reached.
- Absence of pain does not exclude the presence of inflammation.

It has recently been addressed [10] that some of the study shortcomings may relate to the fact that the term "deep lesion" has been used without a more detailed definition of the actual depth of the lesion per se. Was it deep dentine involvement? Is it based on x-rays? Is caries in contact with the pulp clinically, radiographically, or by means of subjective symptoms indicating pain, or is it measured in terms of histology? If this information is missing, it is difficult from a clinical aspect to interpret anything about the pulp.

9.3 Previous Histological Shortcomings Have Simplified the Understanding of Caries Pathology

It should not be underestimated that almost all previous histological studies of the pulp have been based on demineralized histological sections in order to be able to cut thin sections. However, during the decalcification procedure of the tooth specimen, not only the mineral content of the dentine but also the entire enamel is removed. Consequently, important information about the lesion environment has therefore been lost. This may have led to several examples of oversimplification in the understanding of caries pathology:

- Studies attempting to correlate enamel caries with pulpal inflammation have been described as being speculative [11].
- The early spread of caries into the dentine was believed to be the same as seen in advanced stages of lesion progress with signs of huge dentine exposure and undermining enamel [12].
- Teeth with rapidly progressing caries have dominated the materials investigated, presumably because they were the ones available for extraction [6].

Consequently, it was taught that even a small enamel lesion without histological contact to the enamel-dentine junction could induce both the translucent zone and the demineralized zone in the dentine [13] and in particular the non-cavitated enamel lesion could hide bacterial invasion [14] as well as undermine sound enamel from the very beginning, even without visible dentine exposure [12–17]. Therefore, many dentists of the last century were trained to both remove the early enamel lesion by operative intervention, as well as to be radical when performing dentine excavation, because carious dentine left over was believed to maintain the pulp inflammation and eventually lead to pulp degradation. The description of the changes in the pulp has often been closely related to scenarios of "points of no returns" in terms of inflammation. Clinically, the so-called deep caries progression should therefore *not* be treated with an indirect pulp capping [4, 11], as the retained carious tissue would maintain further development of pulp inflammation. In contrast, complete excavation was recommended even if it led to exposure of the pulp, because the pulp was judged to be irreversibly inflamed anyway, even though the patient was not in pain. Moreover, if already an enamel lesion is able to induce inflammation, it would be easy to imagine that a deep lesion would be associated with unwanted inflammation.

However, the advances of pulp biology [18–23] combined with at detailed description of the lesion environment, as well as the clinical evidence of treating deep lesions [24–28], have started to modify the traditional view of pulp inflammation as being "the nonstop train" toward apoptosis and pulp necrosis.

9.4 Progression of the Non-cavitated and Cavitated Enamel-Dentinal Lesion Complex

A brief update of principal caries pathology is presented. Detailed histomorphological studies have revealed that the carious enamel-dentine lesion complex is a closed entity as long as there is no destruction and disintegration of the demineralized enamel [8]. The cariogenic biomass is located at the enamel surface only. The enamel lesion contact with the enamel-dentine junction is strictly related to the extent of the demineralized dentine, and no early spread along the enamel-dentine junction can be monitored (Fig. 9.2a). When the established caries remain untreated, they advance in width and depth. The dentine is clinically exposed (Fig. 9.1c, d) and the biofilm is heavily involving the cavity. The microbial ecosystem can be described as being a "closed" environment. At this stage the spread along the enamel-dentine junction is a characteristic feature undermining sound enamel [29] and the lesion becomes wedge shaped, with the base directed toward the surface (Fig. 9.2b). As the deep lesion further progresses, the undermined enamel often breaks off (Fig. 9.1d–f), due to masticatory forces, converting the lesion environment from a "closed" toward a more "open" lesion environment [30]. Clinically and macroscopically the color of the demineralized dentine becomes darker (Fig. 9.2c), and at the central area the cariogenic biofilms overlying the lesion are markedly reduced. Although the lesion has increased in size, the actual activity has temporarily decreased. Even at the macroscopic level, progressive alterations of pulp inflammation can be observed in terms of increasing visualization of the vascular architecture in the pulp (Fig. 9.2a–c).

9.5 Carious Enamel-Dentine Lesion Complex and Activity: Understanding the Initial Pulp Response Subjacent to Enamel Lesion Without Cavitation

Studies have shown that the cytoplasm/nucleus ratio of the mature odontoblast cells, subjacent the superficial enamel lesion, is more reduced than unaffected control sites, even before visible alteration in dentine mineralization. Moreover,

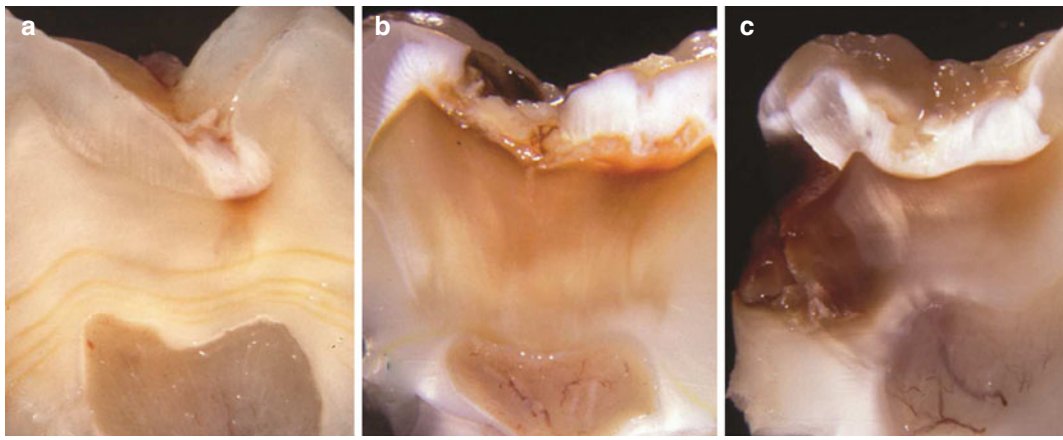

Fig. 9.2 Macroscopical cutting profiles in relation to progressive stages of caries. (**a**) An occlusal lesion without dentine exposure. A close interrelation is noted between the enamel lesion contact and the extent of the affected dentine; no visible alterations in the pulp. (**b**) Macroscopical cutting profile of lesion shown in Fig. 9.1c. Note the retrograde demineralization along the enamel-dentine junction as well as the initial appearance of the pulpal vascular architecture. (**c**) The cutting profile of a mixed lesion environment. Note a more marked appearance of the vascular architecture. From [10] with permission from Elsevier

the subodontoblastic or Höehl's layer appears indistinct [26]. Enhanced mineralization of the dentine is noted in the central and oldest part of the involved lesion area, as the enamel lesion progresses toward the enamel-dentine junction. At the pulpal site substantial growth of the predentine matrix is noted with bundles of collagen fibers aligned with odontoblasts reduced in size [8]. These first findings of cellular alterations and enhanced mineralization of the dentine are probably not associated with antigen-related pulp reactions as the bacterial-induced dentine demineralization is not yet established.

9.6 The Trigger of Pulpal Immunity in Progressive Stages of Carious Dentine

It is well known that the dentine comprises bioactive extracellular matrix [31–35], and during carious demineralization of the dentine, there is a release of bioactive molecules [22, 36, 37], which can trigger the odontoblasts, members of the first line of host defense (see Chap. 7). However, it is unclear whether this may take place even before bacteria have invaded the demineralized dentine (Fig. 9.2a), also defined as affected dentine [38]. In non-cavitated enamel lesions with subjacent dentine demineralization in humans, observations of a reduced odontoblast layer, as well as the alterations in the subodontoblastic region, may qualitatively reflect an early odontoblast-triggered innate immune response [18]. Moreover, a different pulp response is noted subjacent an active versus a slowly progressing lesion. The cytoplasm/nucleus ratio of the odontoblasts appears markedly reduced in both scenarios, but a maintained indistinct subodontoblastic region is noted only in active sites [31].

In a series of *in vitro* studies, the odontoblast-like cells were shown to express Toll-like receptors [39–42] making the cells capable to induce mediators known to influence positively or negatively both the inflammatory as well as the immune responses in pathogen-challenged pulp-like tissue. As an example lipoteichoic acid, which is a by-product from Gram-positive bacteria, was able to elicit proinflammatory cytokines by further promoting immature dendritic cell recruitment [42].

The Gram-positive bacteria represent the first members of invading bacteria in demineralized dentine with a clinical dentine exposure (Fig. 9.2a), eventually accounting for 70 % of the cultivable microbiota in lesion sizes involving two-thirds of the dentine and more [43]. During the development of such a "closed" ecosystem, a remarkable homogeneous lactobacilli microflora can be detected. Gram-negative bacteria take over [44] as the lesion advances, and, because of their content of lipopolysaccharide, they are capable of inducing lipopolysaccharide–binding protein which has an even more complex role in terms of triggering the odontoblast-like cells. Recently, it was found that this protein may interact with lipoteichoic acid, hence reducing the receptor-dependent production of inflammatory cytokines by odontoblast-like cells and in this way modulate host defense in human dental pulp [45]. The various laboratory setups [18–22, 32–37, 39–42] with, for example, the odontoblast-like cells have helped gain more and more complex information, eventually leading to an improved understanding of the host defense as well as of tooth repair in the future. However, we are not there yet, in terms of the application of knowledge transformed into treatment modalities in humans.

9.7 The Dentinal Lesion with Clinical Exposure: The Infected Dentine

The established caries lesion with a visible dentine exposure (Fig. 9.1b, c) will comprise all the classical zones of carious dentine: the zone of sclerotic dentine (i.e., increased intratubular mineralization), the dentine demineralization, and, finally, the zone of bacterial invasion and dentine degradation [8]. When the bacteria invade demineralized dentine and it becomes infected [38], the vast majority of the members of the biofilm are Gram-positive bacteria in primary dentine and the innate immune systems are progressively activated. It is not known how the

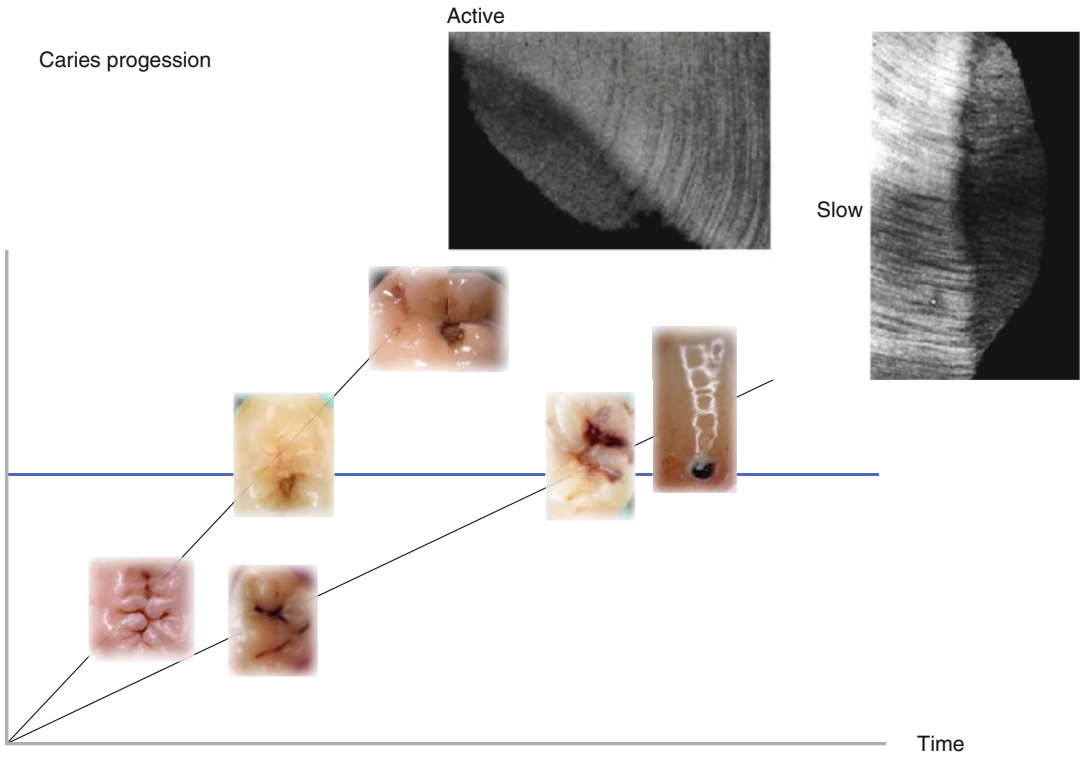

Fig. 9.3 A principal demonstration is shown of an active versus a slow lesion progression. Typically the texture of the tertiary dentine is different within the two scenarios as shown by inserts of two microradiographs of undemineralized thin sections. Along the *x*-axis, the principal caries progression is shown by inserts of clinical illustrations of progressing lesions. The *y*-axis represents the time line. The different slope of the two scenarios reflects the different speed of progression

triggered dental pulp immunity is operating during a slow lesion progression. As tested during stepwise excavation of dentin caries, the cultivable microflora becomes markedly reduced in numbers [46], consequently the acidogenic pH levels decrease, which presumably also leads to decreased production of, for example, lipoteichoic acid. Finally, this may temporarily stop the sequence of events leading to a further unwanted inflammatory response. In confirming this, the tertiary dentine appears like a continuous formation of secondary dentine laid down along a slow lesion progression, whereas the tertiary dentine appears partly atubular during ongoing stages of active lesion progress (Fig. 9.3).

Taken together, the odontoblasts are members of the first line of defense responding to various carious stages and activities. How this modulates the role of the odontoblasts during early tertiary dentine formation in humans remains unclear, but it is detailed in Chap. 10.

9.8 The Definition of Deep and Extreme Deep Carious Lesions

A definition of deep caries has to be made by the x-ray, because it is within the clinical setting that the general dental practitioners will end up using the findings of laboratory research, and therefore it is of paramount importance to have a reference that can be used in a clinical setting. As the depth of the caries lesion represents a diagnostic problem, it may be relevant to further classify it beyond previous attempts. The deep lesion has

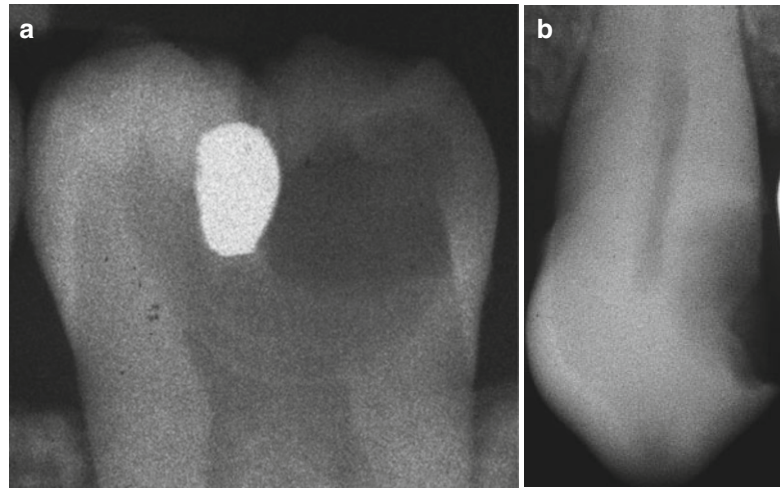

Fig. 9.4 The radiographic presentation of an extreme deep caries lesion versus a deep lesion. (**a**) The entire primary/secondary dentine is penetrated either with no radiodense zone separating the demineralized dentine from the pulp or with a radiodense zone located within the pulp chamber indicative of tertiary dentine. (**b**) The deep lesion involves the pulpal quarter with a radiodense zone separating the translucent zone from the pulp

previously been defined radiographically as being within the pulpal quarter toward actual contact with the pulp [47]. However, we suggest separating the deep lesion in two scenarios. A deep caries lesion is defined as involving the pulpal quarter of the primary/secondary dentine (Figs. 9.4b. 9.5a, and 9.6a) but still with a radiodense zone separating the demineralized dentine [19]. The extreme deep lesion involves the entire primary/secondary dentine either with no radiodense zone separating the demineralized dentine from the pulp or with a radiodense zone located within the pulp chamber indicative of tertiary dentine (Figs. 9.4a, 9.7a, and 9.8a).

These lesions (deep and extreme) may induce initial periapical disturbances/apical periodontitis lesions, which may (Fig. 9.6a) or may not be visible radiographically, but still with the pulp being vital!

9.9 The Further Progression of Deep Caries

Following this radiographically based definition, a deep lesion involves the pulpal quarter of the dentine but still has a radiodense zone separating the pulp and the carious dentine. From a clinical point of view, when bacteria are close to the pulp but are still confined to primary/secondary dentine, pulp inflammatory reactions, even severe, may regress if treatment completely removes the infected and degraded dentinal tissue (Fig. 9.5b, c). There is, to a certain point, a degree of reversibility of pulp inflammation, with tertiary dentin remaining as a permanent "scar" of previous inflammation. However, diagnosing this "borderline-histological-condition" (reversible/irreversible border) by clinical means is very difficult and often misleading. However, it has been known for some time [47] that heavy concentrations of chronic inflammatory cells, macrophages, and a few polymorphonuclear neutrophils (PMNs) represent a characteristic feature beneath the affected dentine tubules in deep lesions. These cells almost obliterate the usual pulp morphology, but liquefaction or coagulation necrosis cannot be found in the pulp (Fig. 9.5c). The inflammatory process is usually confined to the coronal pulp and bacterial cells have advanced to the point of near-exposure. The odontoblasts beneath the affected tubules are very sparse, with no palisading. The coronal blood vessels are engorged. This picture of a long-lasting chronic inflammation has been explained by the fact that the cells in particular macrophages [19] are "frustrated" as they permanently produce cytokines, but without reaching the actual bacteria, because they are still hidden within the carious dentine [8].

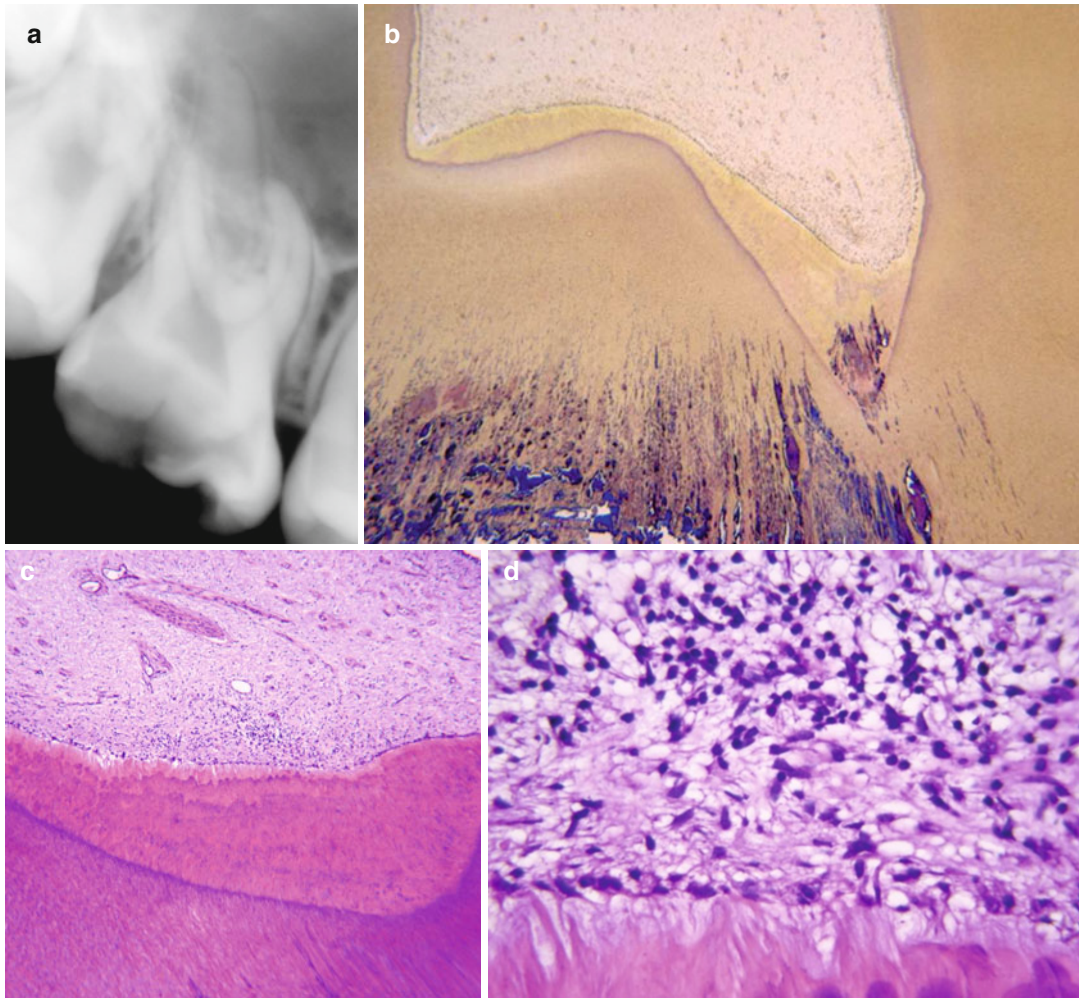

Fig. 9.5 Deep caries is shown with reversible pulp inflammation. (**a**) The caries lesion shown in Fig. 9.1e with a more advanced stage of enamel breakdown due to the undermining nature of caries progression. The patient complained of pain to thermal stimuli and chewing. Sensitivity tests gave exaggerated responses. There is no apical periodontitis lesion. (**b**) Overview encompassing the caries lesion, tertiary dentine and pulp. Note how the tertiary dentine is heavily infiltrated by bacteria in the pulp horn area. No necrosis could be observed in this and in any of the serial sections. The histological diagnosis is "reversible pulp inflammation" (Taylor's modified Brown and Brenn, orig. mag. ×25). (**c**) Considerable amount of tertiary dentine is formed on the pulpal side (H&E, orig. mag. ×50). (**d**) The tertiary dentine is covered by an incomplete layer of flattened odontoblasts. Subjacent to it, a severe concentration of chronic inflammatory cells is present (orig. mag. ×400)

An important aspect related to pulp response is the aforementioned tertiary dentine, which is deposited over the pulpal end of the dentinal tubules centrally affected by caries. During the very active stage of deep lesion progress, where the undermined enamel maintains a "closed" ecosystem, the formation of tertiary dentine may be less pronounced or even absent (Fig. 9.6a, b), and bacterial penetration may be evident in the pulp, even though the caries is not reaching the pulp radiographically. This may be due to the fact that during proximal lesion progress, the cariogenic environment may maintain a high acidogenic environment for a longer period than occlusally,

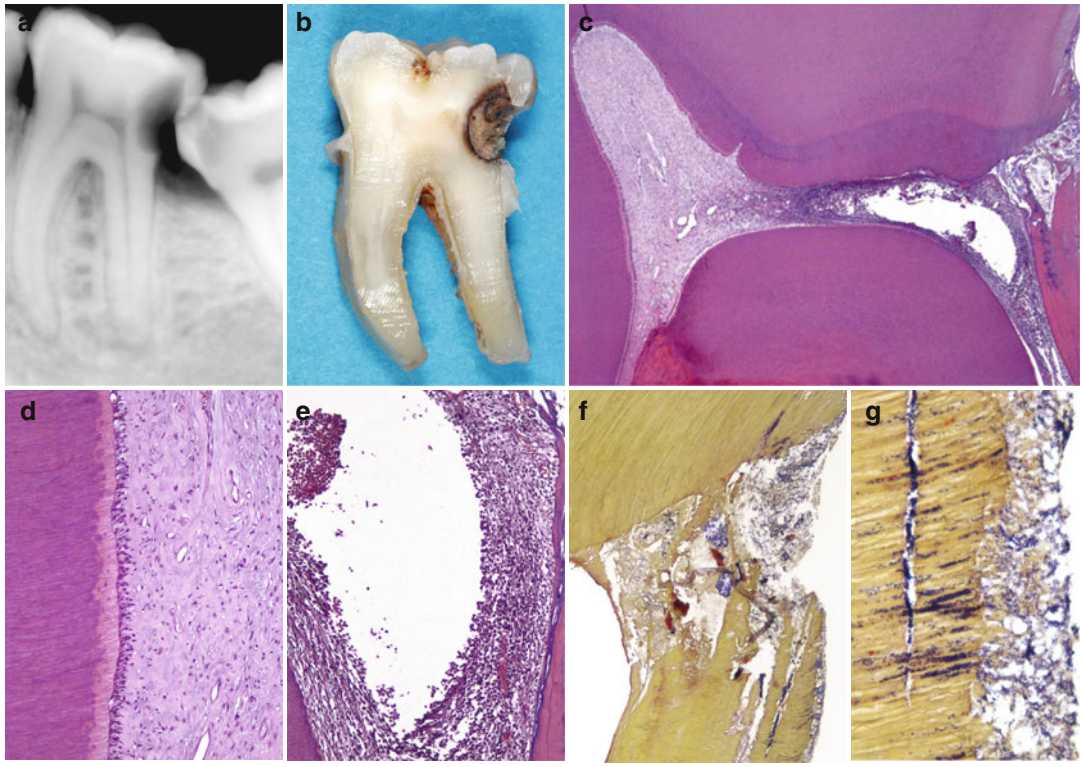

Fig. 9.6 Deep caries is shown with irreversible pulp inflammation. (**a**) Mandibular second molar in a 22-year-old man. Severe spontaneous pain. The radiograph shows a deep distal caries proximal to the pulp. At the distal root there is an indication of an apical periodontitis lesion. The patient did not accept any treatment aimed at conservation of the tooth and requested extraction. (**b**) Photograph taken after grinding the tooth on a mesiodistal plane until the pulp was seen. (**c**) Overview of the pulp chamber. A proximal deep lesion is noted distally. The distal half of the pulp chamber tissue is necrotic, while the mesial portion exhibits a relative normality (H&E, orig. mag. ×16). (**d**) Detail of the left wall of the mesial pulp horn in **c**. The pulp shows normal histological features (orig. mag. ×100). (**e**) Detail of the distal root canal orifice area in **c**. Liquefaction necrosis surrounded by severe concentration of inflammatory cells (orig. mag. ×100). (**f**) Bacterial penetration in the distal pulp horn area (Taylor's modified B&B, orig. mag. ×50). (**g**) High power view of the caries lesion. Dentine is heavily colonized by bacteria. A distinct bacterial biofilm is present on the cavity floor (orig. mag. ×400)

before the undermined enamel gradually breaks down. In addition, the distance toward the pulp may also be shorter.

An active and "closed" ecosystem within the proximal lesion environment is shown in a permanent molar tooth (Fig. 9.6a–g). In this case apical radiolucency is apparent as well, indicative of an apical periodontitis lesion (Fig. 9.6a). A histological study of primary teeth has shown a similar tendency that in subjacent proximal caries lesions, the pulp showed more severe signs of inflammation than compared with occlusal lesions [48].

These observations may also explain why some cases of direct pulp capping fail. If, in the absence of symptoms, during excavation of deep carious lesions, bleeding occurs from a pulp horn, the clinician may decide to perform pulp capping, but the bacteria are in fact "sealed" in the pulp horn. Within recent clinical trials investigating the treatment of well-defined deep caries in adults (using the present definition), it was found very important that excavation did not lead to exposure of the pulp. In case of exposure a pulp capping was performed and the outcome was markedly reduced [24].

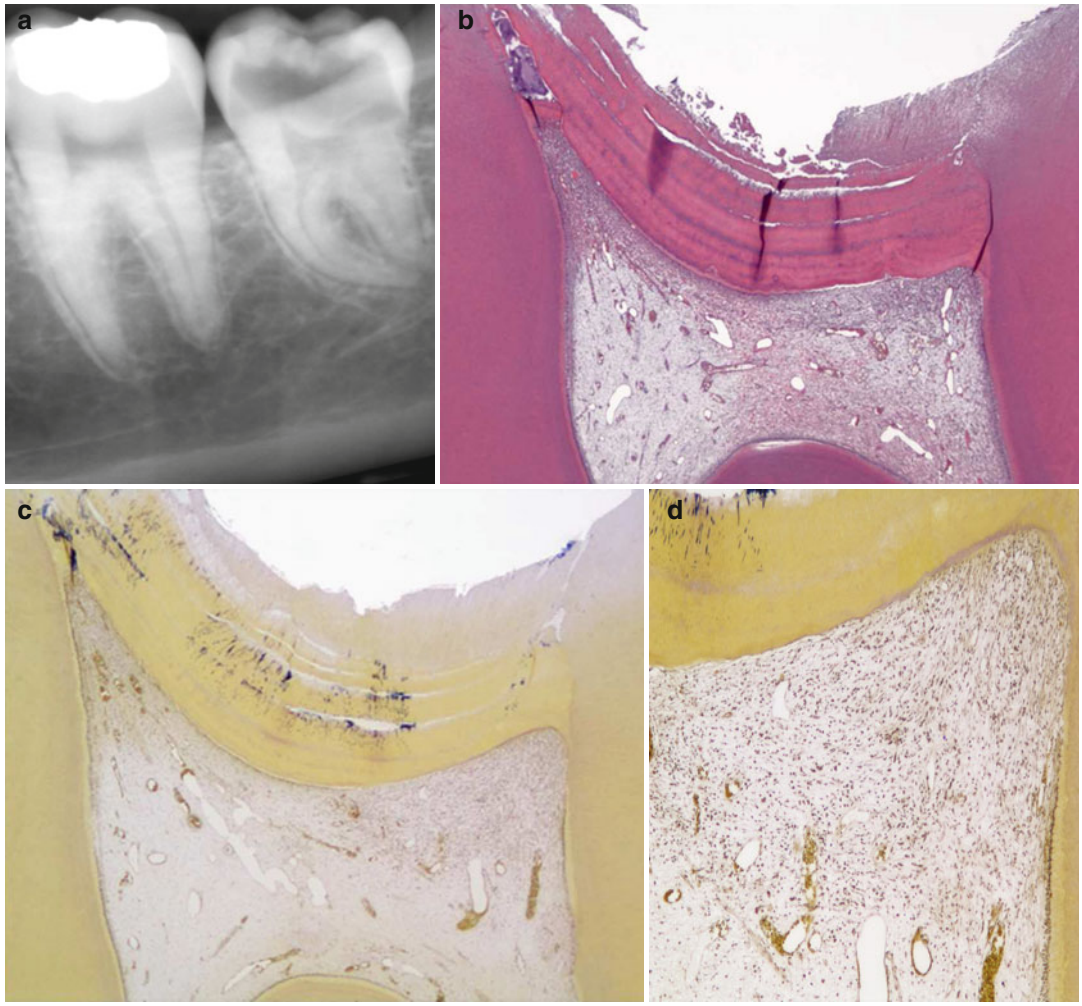

Fig. 9.7 Deep caries and irreversible pulp inflammation are shown. (**a**) Mandibular third molar in a 23-year-old woman. Spontaneous pain. The tooth was extracted. Note that it is classified as an extreme deep lesion. (**b**) Overview of the pulp chamber. Its roof is constituted only by tertiary dentine. No necrosis can be seen in this section (H&E, orig. mag. ×16). (**c**) Section proximal to that in **b** (Taylor's modified B&B, orig. mag. ×16). (**d**) Detail of the distal pulp horn. Severe accumulation of inflammatory cells obscuring the normal pulp architecture (orig. mag. ×50)

9.10 Extreme Deep Caries

During extreme deep caries (Figs. 9.7a–d and 9.8a–g), the bacteria are involved histologically in both peritubular and intertubular dentine. A massive formation of tertiary dentine may be noted, representing the last barrier against bacterial penetration, after the primary/secondary dentine has been completely destroyed (Fig. 9.7b, c). Obvious neutrophil accumulation is occurring (Fig. 9.7c) as bacteria are in direct contact with the pulp tissue reflecting the adaptive immune response [19]. Bacterial invasion of the tertiary dentine per se indicates as well irreversible or unwanted inflammation [49]. In terms of clinical treatment and with a specified treatment protocol which includes the use of magnification, observational studies have actually shown positive outcomes of pulp capping even in extreme deep caries [50].

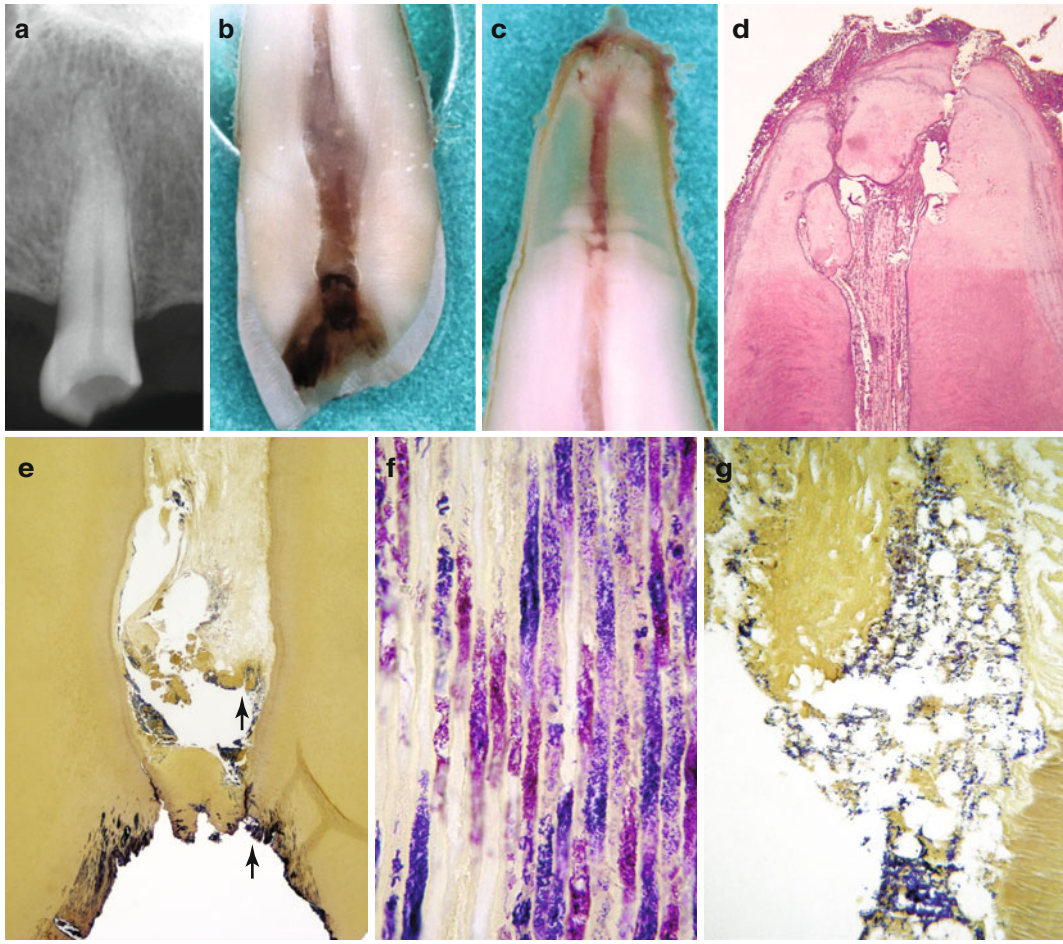

Fig. 9.8 Progression of pulp necrosis is observed. (**a**) Maxillary canine with caries penetrating the pulp chamber in a 61-year-old woman. Spontaneous pain. The tooth was sensitive to percussion. The radiograph shows an absence of the pulp chamber roof and widening of the periodontal ligament space. The patient required extraction of the tooth. The lesion is classified as an extreme caries lesion. (**b**) Photograph taken after grinding the tooth on a buccolingual direction in order to allow proper fixation of the pulp tissue. The pulp tissue in the pulp chamber and in the coronal third appears *dark*, indicating possible pulp necrosis. (**c**) Photograph of the middle and apical third. The pulp tissue appears *reddish* in these areas, indicating the presence of blood and possibly vital pulp tissue. Note the apical ramifications. (**d**) Apical third. The histological section confirms the presence of vital tissue in the apical canal and in the numerous apical ramifications (H&E, orig. mag. ×25). (**e**) Pulp chamber with empty spaces indicating necrosis, the *arrows* are detailed in **f** and **g**. (Taylor's modified B&B, orig. mag. ×25). (**f**) High power view from the carious dentin. Dentinal tubules heavily invaded by Gram-positive and Gram-negative bacteria indicated by the *lower arrow* in **e** (orig. mag. ×1,000). (**g**) Magnification of the area of the right pulp chamber wall indicated by the *upper arrow* in **e**. Dense concentration of bacteria in necrotic tissue (orig. mag. ×400)

9.11 Irreversibility of Pulpal Inflammation

The pulp may be directly exposed by caries, and bacteria have invaded the pulp tissue and a focus of necrosis with limited extension is typically formed in the pulp tissue. It should be emphasized that despite the presence of bacteria in the pulp horn (Fig. 9.8e, f) and a severe acute inflammation in the surrounding areas (Fig. 9.8e, g), the rest of the pulp chamber as well as the radicular pulp may show no signs of inflammation (Fig. 9.8d).

The necrotic area is surrounded by a dense accumulation of PMNs and acellular tissue remnants, indicative of partial liquefaction. Further away from the center of the destruction, there is a typical chronic inflammatory response with a large number of plasma cells, small and large lymphocytes, macrophages, fibroblasts, mast cells, and foam cells.

From a histological point of view, the occurrence of an area of necrosis with bacteria, although of limited extension, constitutes the point of transition from a reversible to an irreversible inflammatory state [51]. It is clear that the treatment of such condition cannot include measures aiming at conservation of the diseased pulp and a more aggressive approach has to be adopted, i.e., full or partial pulpotomy as well as pulpectomy. Once again, from a clinical point of view, the problem lies in our inability to diagnose by clinical means the actual histological condition of the pulp, i.e., the presence of bacteria within the pulp cavity.

9.12 Further Progression of the Pulp Necrosis and Degeneration

The initial area of necrosis slowly expands to involve increasing areas of the coronal pulp. It has to be emphasized that the necrotic tissue colonized by bacteria is clearly demarcated from the adjacent tissue, which continues to be vital and relatively normal (Fig. 9.8a–g). It is important to note that pulp necrosis and infection are slow processes that gradually move in apical direction [51].

9.13 Treatment of Deep Caries and Status of Pulp Inflammation

Know-how on treatment outcomes has improved concerning the treatment of deep caries, because studies and reviews reporting higher evidence have started to emerge [24–28, 52], including longtime data [53, 54], but we are still far from having the best clinical evidence for the objective treatment of actual pulp inflammation.

If a deep or extreme deep lesion progression is present even before the root complex is fully completed, the speed of caries progression must have been quite fast. In a global context, it is known today that the speed of caries progression has been markedly reduced during the past decades [55]. On this basis it could be speculated that the degree of inflammation in "cariously exposed pulps" going back 40–50 years was more often in a severe and irreversible stage of inflammation than in the population of "current pulps." In other words, the rationale and the magnitude of using various treatment modalities of deep caries intervention have started to be modified [56–58]. As examples, the use of less invasive caries excavation approaches in deep caries scenarios has shown that a stepwise excavation also defined as two-step caries removal may be more convenient as opposed to complete excavation in well-defined stages of deep caries [24]. In addition, pulp-capping procedures as well as "full" pulpotomy treatments have started to be reevaluated, and it may become a broader alternative to the vital pulpectomy [59, 60]. Yet, clinical evidence of high quality seems a mandatory prerequisite.

9.14 Summary and Conclusions

In this chapter we have focused on caries as the cause of inflammation, mainly because caries seem to be the most frequent reason for performing a root canal treatment [61]. Other reasons will cause inflammation in the pulp, such as trauma or iatrogenic injuries in general, but the description of these is beyond the scope of this chapter.

The research area of pulp inflammation, repair, as well as regeneration is currently running along a fast track. Histologically, it has long been possible to show the point of irreversibility of pulp inflammation during caries development. How do we apply this information in a clinical setting before it happens and would it be possible to cure unwanted inflammation without

removing the entire pulp? In this context it is important to know:

- The stage of lesion progress (how deep has caries progressed).
- An estimated clinical assessment of the caries activity.
- Estimated age of the caries lesion (approximation of patient age).
- The value of classifying the depth of caries into "extreme deep" as well as "deep" (Fig. 9.4a, b).
- As acidogenic by-products of cariogenic microorganisms are important for the odontoblast triggering of the innate immune response, the simple act of arresting the cariogenic environment does influence the condition of the pulp.
- That treatment of deep lesion (Fig. 9.4b) using a noninvasive excavation approach does not seem to lead to unwanted inflammation, in particular, if the pulp remains unexposed.
- The turn-on of the adapted immune response histologically reflected by a huge accumulation of inflammatory cells demonstrates bacteria either advancing to the point of near-exposure or actual pulp invasion.
- When bacteria have invaded the tertiary dentine in histological terms, the subjacent pulp has become irreversibly inflamed, eventually leading to further apoptosis and pulp necrosis.
- When the radiograph indicates extreme caries (Fig. 9.4a), the bacteria have almost certainly invaded tertiary dentine.
- That extreme deep caries lesion needs a pulp invasive treatment concept.
- Although being at the stage of an extreme deep lesion with focal areas of necrosis and infection, the radicular pulp may be vital.
- The clinical estimation of pulp inflammation remains a challenge.

An obvious goal for pulp inflammation research and for the clinical application is as follows: when would we be able to actively interfere with the pulp host response, by introducing biomolecules which could be used to mitigate the deleterious effects of the cariogenic biofilm? At this time, the simple act of clinically arresting the deep lesion environment by less invasive excavation modalities as well as the treatment of pulp cappings using magnification combined with various applications of base materials comprising bioactivity seems to be efficient approaches (see Chaps. 17 and 19). However, if the bacterial invasion cannot be controlled, it seems impossible to see advances in pulp inflammation and repair research being successfully integrated into a general dental practitioner environment.

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