Cracked tooth is a common dental hard tissue disease. The involvement of cracks directly affects the selection of treatment and restoration of the affected teeth. It is helpful to choose more appropriate treatment options and evaluate the prognosis of the affected tooth accurately to determine the actual involvement of the crack. However, it is often difficult to accurately and quantitatively assess the scope of cracks at present. So it is necessary to find a real method of early quantitative and non-destructive crack detection. This article reviews the current clinical detection methods and research progress of cracked tooth in order to provide a reference for finding a clinical detection method for cracked tooth.

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1. Introduction

Referring to the standards of American Association of Endodontists (AAE), the classification of cracked teeth:(1) Craze lines, the crack is visible which only involves enamel; (2) Fractured cusp, the crack originating from the crown extending to the dentin and terminating at the cervical region; (3) Cracked tooth, the crack extending from the occlusal to the apical direction. (4) Split tooth, the crack that completely splits along the mesial and distal direction and extends to the marginal ridge of the tooth (5) Vertical root fracture and terminating at the cervical region. (3) Cracked tooth, the crack originating from the crown extending to the dentin tooth. Severely pain caused by the release of occlusal pressure is the typical feature of cracked tooth. The location, direction and depth of the crack determine the mode of occlusal pain[13,14]. It should be emphasized that the bite tests may not be able to distinguish pain between maxillary and mandibular origin. Moreover, the application of force is risky to the affected tooth and may cause further crack propagation, so it is sometimes not recommended[15–17].

2.2. Bite test

The sensitivity to temperature stimulation usually indicates that proximal or near-pulp cracks. The high sensitivity to cold stimulation and the positive of bite test can diagnose cracked tooth[14,18]. Kim et al. [19] believed that root canal therapy should be performed when there is obvious cold stimulation pain in cracked tooth.

2.4. Dye test

Dyes can be used to dye cracks in order to see cracks clearly. Commonly used dyes include methylene blue, iodine tincture and gentian violet. However, this method may take several days to see the effect, or even require wearing a temporary crown[18]. Furthermore, the dye test can only detect the location of the crack but have difficulty in assessing progress. Besides, when bacteria enter the crack, the decay is easy to be colored but the dye is difficult to remove, that will affect aesthetics and repair. The toxicological effect of dyes is unknown which limits its application[20,21].

2.5. Transillumination

Transillumination refers to the use of light guide fibers to illuminate the tooth surface and the light perpendicular to the crack will be diffracted, thereby locating the crack[22]. The yellow light is more capable to diagnose cracks[15]. Some scholars have specially designed a crack detection lamp with appropriate brightness which can not only refract at the crack but also facilitate the observation of clinicians[23]. Other studies have also shown that 810 nm diode laser or 1300–1310 nm near infrared laser has good targeting ability for cracks[24–26]. If there is a large area of filling in the affected tooth, the original filling should first be removed to assess the degree of cracking, the condition of the pulp, and the remaining tooth tissue structure[18].

2.6. Microscope detection

It is difficult to detect on naked-eye visual inspection when the crack width is less than 18 µm, and dental surgery microscope can be used to assist in locating cracks[5,27,28].

2.7. Periodontal probing

The presence of separate, narrow, deep periodontal pockets at a site of the suspicious tooth may indicate a hidden crack extending subgingival. The depth of the periodontal pocket may mediate reflect the extension of the crack to the subgingival indirectly. Due to the deep periodontal pocket could also be used as a bacterial invasion route to infect the pulp. Studies have shown that the rate of pulp necrosis is higher for affected teeth with periodontal probing depth greater than 4 mm caused by cracks. Moreover, when the depth of

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4. Conclusion

Conflict of Interest

Acknowledgements

References
narrow deep periodontal pocket was more than 4 mm caused by cracks, that may have a unfavourable prognosis.[3,19].

2.8. Others

2.8.1. Auxiliary diagnosis band

When the above methods still fail to diagnose, a stainless steel orthodontic band can also be worn on the suspicious tooth. If the clinical symptoms of the patients are relieved after 2–4 weeks, the diagnosis is correct. In addition, the band can be used to fix the cleft teeth as external splint[29,30].

2.8.2. Quantitative percussion diagnostics

Quantitative percussion diagnostics (QPD) are commonly used to detect peri-implant osteointegration. And due to the presence of cracks, the tooth tissue on both sides of the crack can be slightly moved under the action of QPD[31], so QPD can be used to detect hidden cracks and locate the presence of cracks that cannot be detected by light transmission, for instance, the cracks where were interproximal or beneath the gingival/bone complex[32,33].

2.9. Imageological examination

Periapical films are commonly used for dental clinical examination, but their ability to identify tooth cracks is not ideal. Cracks can be mediately judged by the situation of periodontal or periapical bone (as shown in Fig. 1)[34]. As a clinical quantitative analysis method at present, Cone Beam Computed Tomography (CBCT) is not ideal for the identification of cracks. Some literatures have pointed out that CBCT is still difficult to identify cracked tooth with a width of less than 50 µm even under appropriate parameters[35]. Guo XL et al. [36] scanned artificial root cracks by combining different voxel parameters with different CBCT units and the experimental results showed that the selected parameters of CBCT affected the identification of root cracks. However, due to the different parameters of each machine and the difficulty of clinicians to adjust the parameters, CBCT is not clinically effective in diagnosing cracked tooth. In addition, studies have shown that cracks are easily secondary to the filling[37], and the filling is generally high-density under CBCT. The influence of filling artifacts makes it more difficult to identify cracked tooth under CBCT[38–40].

3. Quantitative evaluation of cracked tooth

The choice of treatment plan for cracked tooth depends on the stage of the development of the disease, however, the clinical examination methods available at this stage are still arduous to judge the extent of cracks, the relationship between crack and dental pulp, and the subgingival extension. For clinicians, the diagnosis and treatment implementation are difficult problems. Frankly speaking, the judgment of the condition of cracked tooth mostly depends on the subjective analysis of dentists, which will inevitably cause patients’ doubts and misjudgment. The diagnosis and judgment of cracked tooth have always been a long-standing problem[42]. Delay in treatment leads to crack propagation, bacterial invasion leads to pulp infection, and finally causing serious pulp and periodontal disease, which becomes the main cause of tooth loss[43–47]. Therefore, the early diagnosis and treatment of cracked tooth are very important in relieving pain, restoring the function of the affected teeth and improving prognosis. Early detection and diagnosis are important to limit crack propagation[10,48]. It is essential to find a method that can be used for clinical quantitative evaluation of cracked tooth.

Fig. 1. There was no obvious crack image on the apical film, but there was obvious bone destruction around the root of the affected tooth. Extensive bone destruction surrounding the root can serve as a diagnostic reference for root-involved fractures[41].
OCT system can provide extremely high imaging speed too through the speed bottleneck of OCT. SS-OCT uses a longer wavelength for imaging deeper biological tissue penetration. In addition, the swept frequency light source has high transient coherence so that it can achieve a deeper longitudinal imaging range. Moreover, SS-OCT system can provide extremely high imaging speed [61]. Studies have shown that SS-OCT has high sensitivity and specificity in detecting caries and cracked tooth, especially at near-infrared wavelengths of 1310 nm [62, 63]. Both in vivo and in vitro experiments have proved the possibility of SS-OCT for the detection of cracked tooth [63–65]. Although the main experimental subjects were cracks in the enamel layer, the experimental results of Imai K showed that SS-OCT has the ability to recognize the enamel and dentin layer and can identify cracks in the dentin layer. Due to its shallow penetrating depth of about 3 mm, the use of SS-OCT is limited [62]. The ability of SS-OCT to identify full-thickness cracks in tooth hard tissue remains to be promoted [66]. OCT and SS-OCT is difficult to image root crack at sub-gingival zone. In addition, the long detection time, the difficulty of avoiding motion artifacts, limited penetration depth and scanning range, the influence of the special optical characteristics of tooth hard tissue on the detection results and the high cost of equipment are all the difficulties faced by SS-OCT in the detection of cracked teeth [62, 67–69]. At the same time, the contrivance of adaptive probe is necessary with the objective to ensure the operability of oral clinic [70].

3.3. Magnetic resonance imaging

Magnetic resonance imaging (MRI) is a common method of soft tissue examination, which is often used to diagnose temporomandibular diseases and maxillofacial tumors in oral clinics [71]. In recent years, it has also been applied to the diagnosis of dental diseases [72–74]. However, the hard tissue of the tooth has low hydrogen density, less binding water, and short relaxation time that the low signal dental hard tissue shows in MRI, which is difficult to capture. Some scholars use ultrashort echo capture time technology to display the mineralized tissue of tooth, such as sweep image with fourier transformation (Swift) to obtain the clearer signal of tooth hard tissue [75]. In terms of the diagnosis of cracked tooth, the presence of water in the crack produces positive contrast enhancement through two mechanisms: First, the concentration of water in the crack is at least five times higher than that of dentin [76]; Second, the lateral relaxation rate of active water in the crack (=1/t2) is much smaller than the water component confined in the dentin pore, which makes the signal of water in the crack less ambiguous [77]. Tyler. Schuurmans [78] concluded by comparing the MRI and CBCT’s detection results of root cracks in excised teeth after root filling that MRI is better than CBCT in identifying partial hidden cracks and root filling or crown filling has little effect on MRI imaging (as shown in Fig. 2). Djat Idiyatullin et al. [79] used gradient recalled echo (GRE) and SWIFT MRI to detect two tooth cracks in vitro, and the results showed that SWIFT MRI could detect the cracks as small as 20 µm. Generally, MRI examination takes a long time. When examining small volume tissues, routine scanning is prone to artifacts due to patient movement. The research results of Djaudat team also show that the scanning time of SWIFT MRI for cracked tooth can be controlled at about 10 min, which creates a possibility for its practical application in the clinical detection of cracked tooth.

3.2. OCT/SS-OCT

Optical coherence tomography (OCT) is a noninvasive imaging method, which can provide high-resolution cross-sectional images of biological internal tissues [55]. It uses infrared light wave to reflect internal microstructure, which is similar to ultrasonic pulse echo in principle [56, 57]. At present, it has been applied in several clinical departments such as ophthalmology, cardiology and dermatology [58–60]. As one of the derivatives of OCT, swept-source optical coherence tomography (SS-OCT) is an ideal scheme that can break through the speed bottleneck of OCT. SS-OCT uses a longer wavelength for imaging deeper biological tissue penetration. In addition, the swept frequency light source has high transient coherence so that it can achieve a deeper longitudinal imaging range. Moreover, SS-OCT system can provide extremely high imaging speed [61]. Studies have shown that SS-OCT has high sensitivity and specificity in detecting caries and cracked tooth, especially at near-infrared wavelengths of 1310 nm [62, 63]. Both in vivo and in vitro experiments have proved the possibility of SS-OCT for the detection of cracked tooth [63–65]. Although the main experimental subjects were cracks in the enamel layer, the experimental results of Imai K showed that SS-OCT has the ability to recognize the enamel and dentin layer and can identify cracks in the dentin layer. Due to its shallow penetrating depth of about 3 mm, the use of SS-OCT is limited [62]. The ability of SS-OCT to identify full-thickness cracks in tooth hard tissue remains to be promoted [66]. OCT and SS-OCT is difficult to image root crack at sub-gingival zone. In addition, the long detection time, the difficulty of avoiding motion artifacts, limited penetration depth and scanning range, the influence of the special optical characteristics of tooth hard tissue on the detection results and the high cost of equipment are all the difficulties faced by SS-OCT in the detection of cracked teeth [62, 67–69]. At the same time, the contrivance of adaptive probe is necessary with the objective to ensure the operability of oral clinic [70].

3.1. MicroCT

MicroCT has a high recognition rate, which can locate cracks with a width of a few tenths to tens of microns and identify enamel and dentin accurately [49, 50]. Generally, it is used as the gold standard for crack detection in cracked teeth research. However, because of its high restrictions on the volume of the detection sample and the long detection time, it is generally only used in researches [51, 52]. Moreover, MicroCT is not considered as suitable method for diagnosis of tooth crack in routine clinical practice because of the high radiation doses which violates the concept “as low as reasonably achievable” (ALARA) [53, 54].

Fig. 2. (A) MRI can identify some hidden cracks and is less affected by filler artifacts, (B) but the ability to identify hidden cracks is unstable [78, 79].
Therefore, MRI is expected to become a detection method of tooth cracked tooth but the detection sensitivity of MRI needs to be improved and high price for a tooth examination needs to be considered.

3.4. Contrast medium-assisted imaging

Contrast medium is a commonly used imaging auxiliary means, the principle of which is to inject contrast medium into demic tissues or organs to improve the imaging contrast for the sake of achieving the observation purpose [81]. Commonly used contrast include gastrointestinal barium, indocyanine green for retinography and iodine reagent for angiography, etc. This provides a new direction for dental radiography. Theoretically, after the contrast medium is introduced into the crack, the crack is easier to identify when the transmission density under X-ray is higher than that of tooth hard tissue (as shown in Fig. 3). Matthew DL [50] et al. soaked 10 human molars in barium chloride solution and sodium sulfate solution for three days respectively to form BaSO4 precipitate and immerse them in the teeth cracks. The microCT’s ability of identification of cracked tooth after introduction to the contrast medium was improved. Additionally, the results showed that some cracks which could not be detected by ordinary scanning could be detected after dyeing. The results showed that the cracks only involving the enamel could not be identified after BaSO4 staining. It may be acceptable for barium chloride and sodium sulfate to be contained in the mouth. But the excised teeth need to be soaked in the solution for three days in this experiment, otherwise the dye can not completely immerse in the crack or reach the recognition concentration, so it is difficult to meet the identification conditions clinically. Based on the previous experiment [82,83], Li Z et al. used indocyanine green-assisted near-infrared dental imaging to quantitatively detect cracked tooth. The experimental results showed that when using a preestablished detection system and the projection light transilluminates the crack at a vertical angle, the crack depth obtained by analyzing the size of the dark area behind the crack is almost equal to the actual crack depth [84]. Ioversol was also used to assist CBCT in imaging cracks. The results showed that with the aid of Ioversol, CBCT’s ability to identify cracks is significantly improved. This imaging method can only mark the length of crack in the direction of the long axis of the tooth, and the distribution and direction of crack are usually irregular, which reduces the accuracy of the detection results [85]. Yuan M et al. [86] used meglumine diatrizoate (MD) as contrast medium to thoroughly soak 24 excised teeth with artificial cracks, and scanned the isolated tooth model with conventional and enhanced CBCT respectively. The results showed that MD enhanced CBCT could significantly improve the identification ability of cracks. Meanwhile, the team simulated a model of periodontal tissue in vitro. The team pointed out that due to the blocking of periodontal tissue, the contrast agent cannot be immersed into the root cracks, so this method is not suitable for the detection of subgingival cracked teeth. Furthermore, the team also pointed out that how to ensure that the contrast agent is immersed in the crack is also a difficult problem for the technology. Considering that the permeability and fluidity of the contrast medium directly affect the ability of the medium to penetrate the crack, and the saliva environment will affect the concentration of the water-soluble contrast medium as well [86,87], Team of Hu further selected the NaI + DMSO combination which has better permeability. Comparing the identification ability of cracks under CBCT between the new contrast medium combination and previously MD in the saliva environment, it is concluded that the new combination with better permeability has stronger ability to identify crack in the saliva environment [87].

3.5. Nondestructive testing technology

As an essential technology to ensure product quality and equipment safety, non-destructive testing has been widely used in aviation, aerospace, military industry, railway, nuclear power, metallurgy, special equipment, automobile manufacturing, petrochemical and other fields. Conventional nondestructive testing
includes X-ray testing, ultrasonic testing, magnetic particle testing, penetration testing, eddy current testing as well as acoustic emission testing, infrared testing and so on [88]. Some scholars tried to apply these nondestructive testing techniques to the detection of tooth hard tissue (The results of some nondestructive testing for cracked teeth are shown in Fig. 4).

3.5.1. Ultrasonic testing technology
Ultrasonic testing technology is a nondestructive testing method, which has the characteristics of wave length, high resolution and no danger. It is expected to be used in the detection of human teeth [89–91]. Ultrasonic has the ability to penetrate the hard structure and it is very effective in detecting physical discontinuities. It can even detect cracks more narrow than the wavelength, which lays a theoretical foundation for ultrasonic wave to detect cracked teeth. Culjat MO et al. simulated a set of ultrasonic detection system that can be used to detect cracked tooth, which provided a theoretical basis for the application of ultrasonic testing in cracked tooth detection [92]. However, the traditional ultrasonic technology is a contact measurement method, which needs couplant mediated contact. Due to the small dimension of human teeth and the tiny operation space in the mouth, traditional ultrasonic testing is not suitable for tooth testing [93].

3.5.2. Laser ultrasonic technology
Laser ultrasonic (LU) technology is a new nondestructive testing method, which uses pulsed laser to generate ultrasonic and describes the defect characteristics by detecting the reflection, scattering and attenuation of ultrasonic signals [94–96]. The laser can focus on small objects with complex shapes in a non-contact way which solves the problem of insufficient operating space. The laser energy of LU can be kept at a low level to ensure lossless thermelastic operation that making it appropriate for crack detection [93]. Kihhua S [97] preliminarily applied laser ultrasonic nondestructive testing to the detection of cracked tooth, and his team constructed a set of laser ultrasonic testing system which can be used to detect human teeth. They successfully measured the depth of cracks involving the enamel layer on the labial surface of two anterior teeth and the feasibility of the application of LU testing in the detection of cracked tooth was verified by using a three-dimensional finite element model. However, the hard tissue of the tooth is not a single structure and has special optical properties. It is still difficult to successfully establish a complete LU detection system for cracked teeth. In addition, when using LU detection system, we should pay attention to the influence of laser on tooth hard tissue, dental pulp and periodontal tissue. It has been pointed out that some patients may feel pain when locating cracked teeth with semiconductor laser of 810 nm, and the pain of individual patients can last for one second in spite of there is no evidence that the pulp inflammation of individual teeth after several years is directly related to laser irradiation [24]. In addition, laser irradiation can also cause structural damage to tooth hard tissue [98,99]. At the same time, whether the vibration of tooth hard tissue caused by irradiation will extend the crack range needs to be further verified [93].

3.5.3. Optical polarization imaging system
Based on the optical birefringence characteristics of the tooth surface [100], Tien VH et al. [101] constructed an optical polarization imaging system and used this system to detect the excised teeth with cracks. The results show that the system can preliminarily detect the cracks, but the detection results are not completely consistent with the actual depth on the tissue section.

3.5.4. Quantitative light induced fluorescence
Quantitative light induced fluorescence (QLF) is a new optical technology for the diagnosis of dental caries and the detection of dental plaque [102]. Some researchers have tried to use it in cracked tooth detection, and the improved system considers using the maximum fluorescence loss value to preliminarily evaluate depth of crack. The results showed that the maximum fluorescence loss value increases with the increase of crack depth, and there is a close correlation between the crack depth and the maximum fluorescence loss value. The clinical test results show that the improved system is expected to be used in enamel crack detection [103,104].

3.5.5. Photoacoustic tomography
Photoacoustic tomography (PAT) is a new non-destructive and noninvasive biomedical imaging technology, which has been used in enamel crack detection [105].

3.5.6. Anisotropic X-ray dark field tomography
The research of anisotropic X-ray dark field tomography (XTD) provides a theoretical basis for XDT in the detection of tooth cracked teeth [106].
3.5.7. Digital image processing system
In addition, Chunliang Zhang [107] et al. established a set of digital image processing system to simulate the stress change of cracked teeth during chewing, which provides a new reference method for clinical diagnosis of cracked teeth.

3.5.8. Vibrothermography

The principle of Vibrothermography (VibroIR) is that the defect generates heat by friction under ultrasonic vibration. And the defect is detected by the temperature change, moreover, the smaller the crack width is, the more obvious the temperature change is. Matsushita TM [108] et al. tried to detect artificially created cracks extending to the root with different parameters of VibroIR. The experimental results show that the depth of dentin crack can be detected by using VibroIR under appropriate parameters. However, whether vibration will increase the crack range and its effect on dental pulp needs to be considered.

The application of nondestructive testing technology in industry and other fields is becoming more and more mature, and extending it to more disciplines will be the direction that related majors should strive for.

4. Conclusion

Since the quantitative detection of tooth crack can be classified as the nondestructive detection of cracks in hard tissue. The methods that can be used for nondestructive and quantitative detection of cracks could equally apply to cracked tooth. And the special physical and chemical properties of tooth can also be considered as the direction of detection. However, it is due to the special properties of teeth, the multi-layer structure of dental hard tissue, the non-solid structure of dentin and the limited space and time for clinical operation that have brought great difficulties to the detection. In addition, whether routine non-destructive testing is truly non-destructive to teeth, whether the detection will affect the health of the pulp, whether it restricts or affects periodontal tissue, and whether cracks deepen as a result of testing are all questions that should be considered in researches. Therefore, after trying to detect cracks in vitro, it should be used with caution when it is really used clinically.

Conflicts of Interest

The authors declare no conflict of interest.

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