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Research Progress of 3D Imaging Diagnosis of Tooth Fracture Based on CBCT

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Abstract. Cone-beam computed tomography (CBCT) has emerged as a pivotal imaging modality in dentistry, offering three-dimensional visualization with high spatial resolution and flexible parameter settings. Compared with conventional two-dimensional radiographs, CBCT enables detailed assessment of tooth fractures by optimizing voxel size, field of view, and exposure parameters, thereby balancing diagnostic precision with radiation safety. Iterative reconstruction and deep learning-based algorithms further enhance image quality, suppress artifacts, and improve the visualization of subtle fracture lines. Clinically, CBCT provides valuable diagnostic insights for crown fractures, root fractures, cracked teeth, and vertical root fractures, particularly when traditional radiographs are insufficient. It allows accurate evaluation of fracture depth, orientation, and anatomical relationships, while also supporting treatment planning in oral surgery, implantology, and orthodontics. Integration with artificial intelligence holds promise for automated crack detection, image enhancement, and workflow digitalization, significantly reducing operator dependence and diagnostic variability. This review aims to summarize the application value and technical advantages of CBCT in diagnosing various types of tooth fractures, to discuss advances in parameter optimization, artifact reduction, and AI-assisted analysis, and to highlight its limitations and future directions toward standardized and precise clinical practice.

Keywords: CBCT, tooth fracture, artificial intelligence

1. Introduction

Tooth fractures are frequently encountered in cases of dental trauma, structurally weakened teeth following root-canal treatment, and occlusal overload. The spectrum ranges from crown and root fractures to cracked teeth and vertical root fractures. Because fracture lines are often concealed within enamel, dentine, or root-canal walls, conventional two-dimensional radiographs, hampered by structural superimposition and limited contrast, carry a high risk of missed or incorrect diagnoses, leading many patients to undergo extraction only after severe pain or pulpal necrosis has developed. Over the past decade, cone-beam computed tomography (CBCT) has emerged as a focal point in dental imaging research; with voxel resolutions on the order of hundreds of micrometers, multiplanar reconstructions from any angle, and relatively low radiation doses, CBCT offers a new avenue for three-dimensional visualization of tooth fractures.

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Compared with traditional X-ray films, CBCT can provide images with different angles and multiple planes, which significantly improves the visualization ability of complex structures (such as cracks and root canal walls). Additionally, the imaging process is pretty fast and the radiation dose is relatively low, which makes it suitable for high-precision evaluation of local oral structure. Moreover, CBCT clearly displays the depth, direction and position of tooth fracture, and supports preoperative decision-making and intraoperative navigation. In complicated cases such as occult cracks, longitudinal root fractures and re-evaluation after repair failure, it consistently demonstrates superior diagnostic sensitivity. Finally, it can be combined with AI-assisted identification, image enhancement and postoperative follow-up evaluation to promote the digitalization and accuracy of the diagnosis process [1].

However, the routine application of CBCT still faces many bottlenecks. Initially, there is a lack of unified CBCT image interpretation standard, and the consistency among different operators is insufficient. Secondly, problems such as artifact interference, scanning parameter selection and cost-effectiveness have limit its wide routine use. Moreover, the difference between the feature recognition ability of different fracture types and the diagnostic efficiency of traditional methods still needs to be further systematically summarized. This review evaluates the clinical value and technical advantages of CBCT for diagnosing various tooth fractures, examines advances in imaging parameter optimization, crack detection, error control, and standardized interpretation, and analyzes current limitations as well as future optimization pathways for CBCT applications in dentistry.

2. CBCT imaging technology and diagnostic parameter optimization

CBCT is a rotational scanning 3D imaging technique using the conical X-ray beam and the 2D flat panel detector. Its basic principle is that the X-ray source and the detector rotate around the patient to obtain multi-angle 2D projection image data, and reconstruct the 3D voxel image through filtering back-projection or iterative algorithm [2]. Compared with the traditional medical CT, CBCT has significant advantages in spatial resolution of volumetric imaging, while soft tissue has a low contrast, so CBCT is mostly used for oral and maxillofacial examinations that require high anatomical details. CBCT has flexible parameter combinations and it is highly configurable in terms of voxel, field of view, radiation dose and so on, which can meet different clinical needs. For voxels, according to specific needs for observing fine structures, it can be set to a high-resolution mode. The conventional mode is used for full-mouth examination and routine scanning. The setting of scan field of view is related to clinical needs: it generally chooses the small scan field of view for a single tooth and a small area of examination, the medium scan field of view for full-mouth dental examination, and the large scan field of view for full craniofacial and orthodontic analysis. The radiation dose is also various, which depends on the size of the scanning range. For different individuals, it is indispensable to optimize the tube voltage and tube current. Since different individuals have different body shapes, their tube current needs to be adjusted to improve image quality and penetration [3].

The specific parameters of CBCT have direct impacts on image quality and diagnostic efficiency. The most crucial element is the voxel. Smaller voxels can enhance the resolution of the image, making minute fracture traces more apparent, although with the risk of increasing noise. Larger voxels may reduce radiation dose while potentially missing fracture traces. High-intensity current in conjunction with proper exposure time can enhance the precision of fracture display, but it comes with drawbacks like increased radiation dose and motion artifacts. The scanning range should be restricted to the target area to ensure high precision. An unnecessarily large range not only increases scattering and decreases image resolution but also elevates radiation exposure and exacerbates

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motion artifacts [4]. Utilizing iterative reconstruction algorithms can reduce noise and artifacts, which enhance the contrast and visualization capabilities of tooth fractures. To minimize imaging errors, it is essential to employ appropriate parameters combined with strictly fixed patient positioning, in order to achieve maximum diagnostic accuracy and radiation safety.

For image processing and reconstruction, the integration of iterative reconstruction and deep learning can further optimize image quality and eliminate artifacts [5]. Image reconstruction is to use statistical or model iterative algorithms, which can effectively remove noise and scatter artifacts while preserving anatomical details through regularization constraints. In clinical optimization reconstruction, hard synchronization and soft algorithm matching enhance the image quality at low doses [6]. In the future, physics-based embedded end-to-end interpretable AI algorithms, when integrated with dynamic imaging, may enable CBCT to support personalized diagnosis and treatment as well as real-time organ monitoring in precision medicine.

3. Clinical value of CBCT in diagnosis of types of tooth fracture

The application of CBCT exhibits distinct characteristics in various types of tooth fractures, including crown fractures, root fractures, cracked tooth, and vertical root fractures [7,8]. For the diagnosis of crown fracture, CBCT has the advantage of providing diagnostic information for complex cases, which is difficult for traditional apical radiographs. For root fracture, 3D imaging can capture the fracture line and its spatial relationship between pulp cavity and root filling material, in order to provide crucial references for whether to preserve or extract the tooth. For fractured tooth, CBCT thin-slice reconstruction can capture tiny tooth fractures. Although the direction of crack and the tilt of the scanning plane have limitations on detection, multiplanar reconstruction allows analysis of suspicious cracks from multiple angles. Vertical root fracture is the most complex type of tooth fracture, often being diagnosed at a later stage [9]. CBCT images often acquire typical separation of fractured segments. Although there is a risk of false-negative, combining the history of occlusal pain with indirect signs such as an increased periodontal ligament space can increase the accuracy of diagnosis. It is also important that metal artifacts in CBCT can obscure fractures after full crown restoration [10]. In this case, it needs to be judged in combination with clinical examination.

The sensitivity of CBCT 3D imaging and high spatial resolution for early caries lesions, tiny apical fracture, root resorption and other lesions is higher than that of traditional X-ray 2D imaging, especially for complex anatomical locations, which can reduce the impact of structural overlap [11]. However, its specificity may be lower compared to traditional X-ray due to excessive sensitivity, leading to false-positives in estimations of bone density. The 3D information of CBCT clinical decision-making can evaluate the lesion range more accurately, and this is helpful to formulate individualized treatment plans. However, traditional X-ray is still widely used in clinical because of its simple operation and low cost. In addition, the application of CBCT 3D imaging in oral surgery, implant and orthognathic surgery has proved its value in preoperative anatomical evaluation, risk avoidance and postoperative healing monitoring [12]. CBCT can explicit the 3D relationship between tooth roots and neovascularity, assess bone quality and bone resistance, and track bone healing through quantitative reconstruction after surgery. Besides, CBCT provides a more comprehensive imaging basis for the diagnosis and treatment decision of tooth fracture, but its optimal indications and usage process still need standardization by evidence-based guidelines.

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4. Digitization of AI-assisted identification and diagnosis processes

In recent years, image fracture detection technology based on deep learning, automatic annotation technology based on semi-supervised learning, and image enhancement technology with image super-resolution algorithm have been used in fracture detection and analysis. Some network models have good performance in the identification and detection of complex fracture, and with the help of deep learning technology, the problem of insufficient small fracture detection samples is solved by synthesizing high-quality images. In oral and maxillofacial surgery, implants, restorations, orthodontics and other difficult cases, CBCT 3D anatomical details have become an important diagnostic tool for these cases, which provides interpretation of bone structure, root morphology, neural tube travel, and even the area of the lesion [13]. However, in the cases like complex structure, subtle lesions or ambiguous boundaries, barely relying on manual identification of CBCT data is not only time-consuming and laborious, but also allows for subjective or missed diagnosis. AI-assisted technology can greatly solve these problems, it can process huge CBCT data, quantify tiny densities invisible to human eyes, analyze complex anatomical structures, and automatically perform 3D intelligent analysis. The combination of AI and CBCT can improve the diagnostic accuracy and work efficiency of complex cases, reduce misdiagnosis, and give dentists an objective basis for judgment [14]. However, the interpretability, cross-device generalization ability, and clinical proving are still prerequisites for widespread application.

5. Challenges and future direction

Although the application of CBCT in the diagnosis of tooth fractures has shown many advantages, it still faces significant challenges in the clinical. Firstly, it lacks standardization for tooth fractures, subtle differences in parameters can lead to insufficient reproducibility and comparability of the results. Secondly, the identification of fracture images depends on operator's experience and subjective judgment, especially in cases of small fractures, hidden fractures and metal repairs, it is difficult to ensure the consistency of image interpretation. In addition, the high cost of CBCT equipment, maintenance and operators' training make it difficult to popularize. Meanwhile, the clinical value of CBCT is still lack of large-scale, multi center , evidence-based research support in some tooth fracture diagnosis. To solve above problems, future developments should focus on the optimization of CBCT imaging technology, such as iterative reconstruction algorithms and dynamic artifact suppression, in order to improve the quality of diagnostic image while reducing patient radiation exposure. Moreover, lowers the threshold for operation and improves accuracy and objectivity by using AI-assisted technology. From an experience-based imaging tool to an intelligent and standardized diagnostic tool. Thus, in the future, CBCT should realize the routine and precision of tooth fracture diagnosis under the premise of ensuring radiation safety [15,16].

6. Conclusion

Compared with traditional two-dimensional imaging, CBCT can display the structure of tooth tissue better, especially in the diagnosis of complex cases. However, there are still many problems with CBCT, since it is lack of standardizations for parameters; it relies too much on dentists' experience; it is expensive and it is difficult to control artifacts and radiation dose. In the future, CBCT needs to reduce radiation dose and establish unified diagnostic standardizations. At the same time, it will be combined with AI assisted technology, which greatly helps to improve the efficiency and accuracy of diagnosis of tooth fractures.

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