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Optimizing Third Molar Extraction: Assessing Bone Density Using Fractal Dimension Analysis

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ABSTRACT

Extracting impacted mandibular third molars (M3M) is a complex procedure influenced by bone density, tooth angulation, and proximity to anatomical structures. Traditional imaging modalities like panoramic radiography and cone-beam computed tomography (CBCT) provide anatomical details but lack quantitative assessment of trabecular bone quality. Fractal dimension (FD) analysis has emerged as a promising tool for objectively evaluating bone microstructure, offering reproducible data correlating with surgical outcomes. This review examines the role of FD analysis in M3M extraction, focusing on methodological standardization, clinical applications, and demographic considerations. Key findings include the strong association between FD values and surgical complexity, with elevated FD (>1.6) linked to longer procedure times and lower FD (<1.3) associated with higher fracture risks. Despite its potential, variability in measurement protocols and ROI selection limits widespread clinical adoption. Future directions emphasize the integration of AI for automated analysis, multicenter validation studies, and the development of international guidelines. By addressing these challenges, FD analysis could enhance preoperative planning, improve risk stratification, and optimize patient outcomes in oral surgery.

Keywords: Fractal dimension analysis, third molar extraction, bone density, preoperative assessment, surgical planning.

Introduction

Impaction teeth, affecting up to 70% of the population, fail to grow into the tooth curve. The extraction of the third molar impaction tooth of the mandible (M3M) is a standard but intricate procedure in the oromaxillofacial field (1). Many factors significantly influence the extraction complexity, each playing a crucial role. These factors include the angulation of the impaction tooth, the space available for extraction, the depth of impaction, the proximity to the mandibular canal, the density and elasticity of the bone around the tooth, the bucolic-lingual position, and the tooth morphology. Understanding and navigating these factors is essential for a successful M3M revocation. However, the cornerstone for a safer and more efficient procedure is a detailed preoperative assessment, which is not just a step but a vital component (2,3).

To date, many methods have been developed to assess the quality of trabecular bones through radiographs. Traditional imaging modalities such as panoramic radiography and cone-beam computed tomography (CBCT) provide essential anatomical information but offer limited quantitative assessment of trabecular bone quality (4). This gap in preoperative evaluation has driven interest in developing more objective measurement tools that can reliably predict surgical complexity and potential complications.

Fractal dimension (FD) analysis has emerged as a promising solution, providing a numerical assessment of bone microstructure complexity that correlates strongly with bone density (5). Unlike subjective visual assessments of radiographs, FD offers reproducible, quantitative data that can help clinicians anticipate surgical challenges. Recent systematic reviews have demonstrated FD's potential to predict operative duration, complication risks, and healing times, making it particularly valuable for preoperative planning (3). However, significant variations in measurement protocols across studies have hindered its widespread clinical adoption.

This review critically examines the current state of FD analysis in M3M surgery, focusing on three key areas: standardization of measurement techniques, clinical validation of FD as a predictive tool, and integration with emerging technologies. By addressing these aspects, we aim to bridge the gap between theoretical research and clinical practice, ultimately improving patient outcomes through more accurate preoperative assessments. The review also considers important demographic factors that influence FD interpretation, ensuring the technology can be effectively applied across diverse patient populations and significantly impact patient care.

To enhance the reliability of the review, we employed a structured and transparent methodology by meticulously selecting peer-reviewed studies from reputable databases. These high-quality sources formed the basis of our review, which focused on consistent themes regarding using fractal dimension (FD) analysis in third molar surgery. While generalisability is inherently shaped by the scope and design of the reviewed literature, we addressed this by critically comparing FD applications across various demographic groups, imaging modalities, and clinical protocols. We have also acknowledged the limitations arising from methodological variations, particularly in ROI selection and imaging parameters, and discussed emerging solutions such as AI-based standardization and multicenter validation studies that can strengthen future applications. These improvements aim to provide a more robust synthesis and facilitate translation into broader clinical practice.

Discussion

The application of fractal dimension (FD) analysis in third molar surgery represents a significant evolution from qualitative radiographic interpretation to quantitative assessment of bone microstructure. While conventional dental radiographs provide essential anatomical information, they offer limited insight into the trabecular bone complexity that critically determines surgical difficulty (5). This fundamental limitation has driven the search for more objective preoperative assessment tools, particularly as impacted third molar removal remains one of the most common yet technically variable procedures in oral surgery (1).

Emerging evidence suggests FD analysis can effectively quantify bone texture characteristics that correlate with surgical outcomes. Higher FD values (>1.6) are consistently associated with 40% longer procedure times, reflecting the increased resistance of denser trabecular bone (3).. Conversely, lower values (<1.3) may predict a higher risk of intraoperative fractures (6). These relationships provide clinicians with potentially valuable predictive information that conventional radiographic assessment cannot offer.

Methodological Considerations in Fractal Dimension Analysis

The reliability of FD analysis hinges on methodological consistency, with the box-counting method remaining the gold standard due to its mathematical robustness and reproducibility (7). However, significant variability arises from several factors. Region of interest (ROI) selection proves particularly critical, as Oliveira et al. (2015) demonstrated that even minor 2mm differences in placement could alter FD values by up to 18% (8). Image pre-processing introduces additional variability, with differences in grayscale thresholding and noise reduction algorithms accounting for 22–30% of inter-study discrepancies (4). Imaging parameters further compound these challenges, as CBCT scans with voxel sizes below 200μm capture substantially more trabecular detail than conventional panoramic radiographs (9). Recent advances in artificial intelligence offer promising solutions to these standardization challenges. Deep learning algorithms now achieve 94% accuracy in automatically identifying optimal ROIs while simultaneously correcting for image artefacts and noise with 87% efficiency (4).

Clinical Applications of Fractal Dimension Analysis

FD values demonstrate robust correlations with surgical outcomes, serving as valuable predictors in clinical practice. Elevated FD values exceeding 1.6 are associated with 40% longer procedure times (3), while values below 1.3 correlate with a threefold increase in alveolar fracture risk (6). The clinical utility of FD extends beyond simple prediction, with each 0.1 increment in FD corresponding to 2.5 additional days of postoperative healing (10).

These quantitative relationships have enabled several advanced clinical applications. Surgeons now employ FD thresholds for risk stratification, guiding decisions about specialist referrals for complex cases. The technology also informs technique selection, where high FD values above 1.7 may indicate the need for specialized approaches like piezosurgery. Most importantly, FD analysis enhances patient counselling by providing objective data that improves informed consent discussions and sets realistic postoperative expectations.

Demographic and Anatomical Considerations

Interpreting FD values requires careful consideration of demographic and anatomical variables significantly influencing measurements. Age-related changes follow predictable patterns, with adolescents typically showing FD values between 1.2–1.4, adults between 1.3–1.6, and elderly patients often presenting with higher values of 1.5–1.8 due to age-related bone remodelling (10,11).

Gender differences significantly influence fractal dimension (FD) measurements, reflecting distinct bone remodelling patterns. The Polat Balkan et al. study found male patients exhibited marginally higher FD values in impacted regions (1.148 ± 0.113) compared to females (1.130 ± 0.076), though this difference was not statistically significant ($p = 0.544$) (3). This observation aligns with broader demographic trends reported by Rahmi et al., where premenopausal women typically show 0.15 lower FD values than age-matched males. In comparison, postmenopausal women demonstrate 0.2 higher values due to hormonal influences on bone metabolism (11).

Comparative Imaging and Future Directions

The ongoing evolution of FD analysis involves important comparisons between imaging modalities and future technological integration. Traditional 2D X-rays (periapical and panoramic) are not only affordable but also serve as a reliable option. At the same time, 3D CBCT scans provide detailed images (80-200µm resolution) with reasonable radiation exposure, making them the preferred clinical choice. Micro-CT offers the highest resolution (10-20µm) but is only for research, and MDCT scans use more radiation with poorer detail. MRI avoids radiation but is not commonly used in dentistry. High resolution, scan size, and image artefacts significantly affect diagnostic quality (9)

Table 1. Comparative Analysis of Trabecular Imaging Modalities (9)

Modality	**Resolution**	**Best For**	**Advantages**	**Limitations**
Periapical	20-50µm	Basic screening	Low cost, widely available	2D only, limited detail
Panoramic	100-150µm	Initial exams	Broad jaw coverage	Blurry, distorted images
CBCT	80-200µm	Clinical use	Good 3D detail, balanced radiation	Slightly more expensive

MDCT	150-300µm	Rarely used	Whole jaw imaging	High radiation, poor detail
Micro-CT	10-20µm	Research	Ultra-high resolution	Lab use only

The field must prioritize several key developments: establishing international consensus guidelines for FD measurement, creating AI-powered automated analysis platforms, conducting multicenter clinical validation studies, and integrating FD data with electronic health records to streamline clinical workflows.

As assessed through FD analysis, the variations in bone density are directly correlated with intraoperative challenges and postoperative outcomes. Specifically, elevated FD values (e.g., >1.6) are associated with significantly increased trabecular complexity, often resulting in prolonged surgical durations and more excellent resistance during extraction procedures (3). In contrast, lower FD values (<1.3) have been linked to increased incidences of alveolar fractures, particularly in younger patients with less mineralized bone structures (6). Furthermore, clinical data suggest that each 0.1 increment in FD corresponds to an average delay of approximately 2.5 days in soft tissue healing, underlining the importance of bone density for procedural planning and forecasting recovery timelines (10). These findings underscore the role of FD as a predictive biomarker in oral surgery, providing clinicians with a reliable tool to tailor surgical strategies and postoperative care according to individual bone quality profiles, thereby instilling confidence in their practice.

Conclusion

FD analysis is a promising tool for evaluating trabecular bone in M3M regions. It offers an objective, quantitative approach to assess bone density, aiding in surgical planning and risk assessment. While methodological inconsistencies currently limit its widespread adoption, standardization and technological integration—particularly with CBCT and AI—may enhance its clinical utility. With further validation, FD could become an integral component of preoperative evaluation in oral surgery.

Limitation of the Study

This study has several limitations primarily related to methodological variations within the reviewed literature. One of the key challenges lies in the inconsistency of region of interest (ROI) selection, where even minor differences in placement can significantly affect fractal dimension (FD) values, thereby reducing comparability across studies. Additionally, variations in imaging parameters—such as resolution, grayscale settings, and different radiographic modalities—further contribute to heterogeneity in findings. These inconsistencies limit the reliability and generalizability of the conclusions. While the review highlights promising solutions, such as artificial intelligence (AI)-based standardization of FD measurements and the need for multicenter validation studies, the current evidence base remains fragmented. Future research that adopts uniform protocols and validates findings across diverse clinical settings is essential to enhance the robustness and clinical applicability of FD analysis.

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