SYSTEMATIC REVIEW

Use of fractal analysis in dental images: a systematic review

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Objectives: This study reviewed the use of fractal analysis (FA) in dental images.

Methods: A search was performed using PubMed, MEDLINE, LILACS, Web of Science and SCOPUS databases. The inclusion criteria were human studies in the English language, with no date restriction.

Results: 78 articles were found in which FA was applied to panoramic radiographs (34), periapical radiographs (21), bitewing radiographs (4), cephalometric radiograph (1), cone beam CT (15), micro-CT (3), sialography (2), and ultrasound (2). Low bone mineral density (21) and systemic or local diseases (22) around the bone of dental implants were the main subjects of the study of FA. Various sizes and sites of the regions of interest were used to evaluate the bone structure. Different ways were used to treat the image and to calculate FA. FA of 43 articles showed significant differences in the comparison of groups, mainly between healthy and sick patients.

Conclusions: FA in Dentistry has been widely applied to the study of images. Panoramic and periapical radiographs were those most frequently used. The *Image J* software and the box-counting method were extensively adopted in the studies reviewed herein. Further studies are encouraged to improve clarification of the parameters that directly influence FA.

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Introduction

Fractal analysis (FA) is a mathematical method by which irregular and complex body structures may be evaluated. The quantitative outcome of this method is defined as the fractal dimension (FD).[1,2] Since 1875, when du Bois Reimond first introduced the concept of continuous non-distinguishable functions, FA has been further improved and used by researchers.[3] Mandelbrot published information on sets of mathematical functions used to describe complex geometrical structures and the term "fractal" was consolidated.[3–5] Fractal is derived from the Latin "fractus" which means "fractured" or "broken." The fractal method is different from conventional geometry and is used to evaluate similar forms on various scales.[6] True fractals go beyond physical form; they can be temporal or spatial on infinite scales and repeated pattern. Digital images are limited by screen resolution. They are not true fractals in a strict sense, but approximations of these fractals. In a magnified image with N structures, a greater number of details is observed, but the number of structures remains the same. To measure the complexity of these structures, it is necessary to count the number of parts on a well-defined scale. Then, the FD formula considers the number of parts and a magnification scale. Mathematically, it is expressed by $D = \log n / \log \varepsilon$, where N is the number of parts and ε is the defined scale.[7,8]

Medicine and its allied specialties have adopted FA since it can be broadly applied to the analysis of image examinations. In dentistry, the assessment of the bone

pattern of the jaws in dental radiographs is the main outcome evaluated using FA. Researchers who investigate bone mineral density (BMD) have also benefited from this method for the quantitative assessment of trabecular bone. However, in recent years, the fractal method has been employed in several studies in which bone structures have been explored.[9–12]

Fractals may be calculated from digitalized images, but pre-processing of these images is necessary. Based on medical images, White and Rudolph[13] described a computer program that measures the morphologic features of trabecular bone. In their study, the authors detailed the steps of image standardization to highlight trabecular bone. The public domain software *ImageJ* (available at https://imagej.nih.gov/ij/) was used. After image acquisition, high-resolution and compressed images were saved to prevent variations. The sequence included cropping of the regions of interest (ROI), duplication of the ROI and removal of large-scale variations in brightness with a blurred Gaussian filter (sigma = 35 pixels, kernel size = 33×33). The subtraction of ROI from the original image, the addition of 128 grey values to each pixel location, binarization, erosion, dilatation, inversion and skeletonization were also events in this sequence.

After image preparation, some methods of FD calculation, such as power spectral density, triangular prism surface area, the blanket method, and intensity difference scaling or the variogram can be used.[5] The box-counting algorithm, considered to be easily accessible, was the method most frequently used.[14–16] Among the methods of morphological description of the trabecular architecture, FD is a mathematical tool that allows the radiologist to predict the quality of bone tissue.[15] This technological advance facilitates access to high-standard images; the digital images are a high-precision image modality available for the quantitative evaluation of the bone microarchitecture.[11]

In dental clinical practice, radiographic images are often ordered by the healthcare provider as complementary exams. Methods such as FA, that objectively quantify changes in bone pattern arising from a disease or the progression of treatment, are important and indispensable for clinical and scientific investigations. In this scoping review, we aimed to present studies describing the applications of FA to different types of dental images and their main findings. However, no review summarizing the body of evidence about FA has been conducted thus far. A review of this topic would be helpful by updating the practitioner regarding the use of FA in dentistry. Therefore, with this scoping review, we aimed to present studies describing the applicability and the usefulness of FA as a tool for the evaluation of bone structures in dental images and to illustrate the methods and results obtained in the included articles.

Methods and materials

The reporting of this review was in agreement, wherever possible, with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis.[17]

Eligibility criteria

Original research articles in which FA was used as an evaluation tool for texture analysis in dental images were eligible for this scoping review. Only studies published in English were included. There was no publication date restriction.

Articles on FA applied to areas other than dentistry, letters to the editor, case reports and literature reviews were excluded. Studies conducted on animals, dry mandibles, bone models, cadavers and studies in which other materials such as tissue fragments or histological slices had been used were also excluded. A summary of the inclusion and exclusion criteria is provided in Table 1.

Information sources and search strategy

Electronic searches were undertaken using PubMed, MEDLINE, LILACS, Web of Science and SCOPUS databases from their date of inception until the second week of June/2018. An update was conducted in December 2018. The search strategies used in the electronic databases are displayed in Table 2. The references retrieved from each database were exported to the Reference Manager software (Reference Manager, Thomson ISI, Thomson Reuters, Toronto, Canada). Duplicate hits were removed upon identification.

Study selection

Two review investigators (oral and maxillofacial radiologists) assessed the title and abstract of each article in

Table 1 Inclusion and exclusion criteria of the studies

	Inclusion criteria	*Exclusion criteria*
Study design	Observational studies, clinical trials and accuracy studies	Letters to the editor, case reports and literature reviews
Area of interest	Dentistry	Areas other than Dentistry
Method evaluated	Fractal analysis	Other analysis
Language	English	Other languages
Publication date	No restrictions	-
Participants	Humans	Animals, dry mandibles, bone models, cadavers and studies in which other materials, such as fragments or histological tissues were used

Table 2 Search strategy for each each electronic database

Database	Keywords	Search 1[a]	Updated Search[b]
		Results	
Pubmed	Fractal AND radiology OR image OR imaging OR periapical OR panoramic OR CBCT OR tomography OR X-ray OR X-ray OR microtomography OR micro-CT OR cone beam computed tomography OR cone beam tomography OR "radiograph" OR radiography OR "bite wing" OR bitewing OR bite-wing OR cephalometry OR ultrasound OR doppler AND dentistry OR dental OR maxillofacial OR oral OR jaw OR mandible OR maxilla OR mandibular OR odontology	166	14
Medline	Fractal AND radiology OR image OR imaging OR periapical OR panoramic OR CBCT OR tomography OR X-ray OR X-ray OR microtomography OR micro-CT OR cone beam computed tomography OR cone beam tomography OR radiograph OR radiography OR bite wing OR bitewing OR bite-wing OR cephalometry OR ultrasound OR doppler AND dentistry OR dental OR maxillofacial OR oral OR jaw OR mandible OR maxilla OR mandibular OR odontology	135	6
Scopus	Fractal AND radiology OR image OR imaging OR periapical OR panoramic OR CBCT OR tomography OR X-ray OR "X-ray" OR microtomography OR "micro-CT" OR "cone beam computed tomography" OR "cone beam tomography" OR radiograph OR radiography OR "bite wing" OR bitewing OR bite-wing OR cephalometry OR ultrasound OR doppler AND dentistry OR dental OR maxillofacial OR oral OR jaw OR mandible OR maxilla OR mandibular OR odontology	207	13
LILACS	Same as Pubmed	25	5
Web of Science	Same as Pubmed	170	7
Total		703	45

CBCT, cone beam CT.
[a]Up to the second week of June 2018
[b]From the third week of June 2018 to the first week of December 2018

the first screening. The articles with titles and abstracts that met the eligibility criteria were included. The full texts of publications with titles and abstracts with insufficient information for a decision about inclusion or exclusion were retrieved for a second screening. In the second screening, the full texts retrieved were evaluated taking into account the same eligibility criteria as those considered in the first screening. Those that met the eligibility criteria were also included. During the study selection, disagreements between review investigators were resolved by means of a discussion until a consensus was met. If no consensus was met, a third review investigator (a senior lecturer in Oral and Maxillofacial Radiology) was consulted and provided the final decision regarding inclusion or exclusion.

Data extraction and data items
Data were extracted independently by the same two review investigators using a predesigned Word data form. The following data were extracted from each study: first author's last name, year of publication, objective of the study, dental exam, sample size, ROI (shape, size and site), method for FA calculation, FD values, and the main results regarding FD. Any discrepancy was resolved by discussion between the two review investigators.

Results

Study selection
The searches retrieved 748 references identified across the five electronic databases. After the removal of 454 duplicates, 293 titles and abstracts were screened. Of the 293 references evaluated during the study selection, 78 met the eligibility criteria and were included in this review. The flow chart (Figure 1) displays the process of study selection in its entirety. A summary of the studies with the FA of three most common dental images and their main findings are described in Table 3. Data of the 78 included articles are summarized in the Supplementary table.

Study characteristics
The first article using the FA method was published in 1991.[18] Most articles (*n* = 51) were published after 2011 (Figure 2). Regarding the type of study, most were observation studies (*n* = 68), 36 of which included a comparison group, 13 were cross-sectional studies and 19 follow-up studies. Eight accuracy studies and two clinical trials were also found. Low BMD (21 articles) and other systemic or local diseases (22 articles) were the main issues evaluated in these studies (Figure 3). The
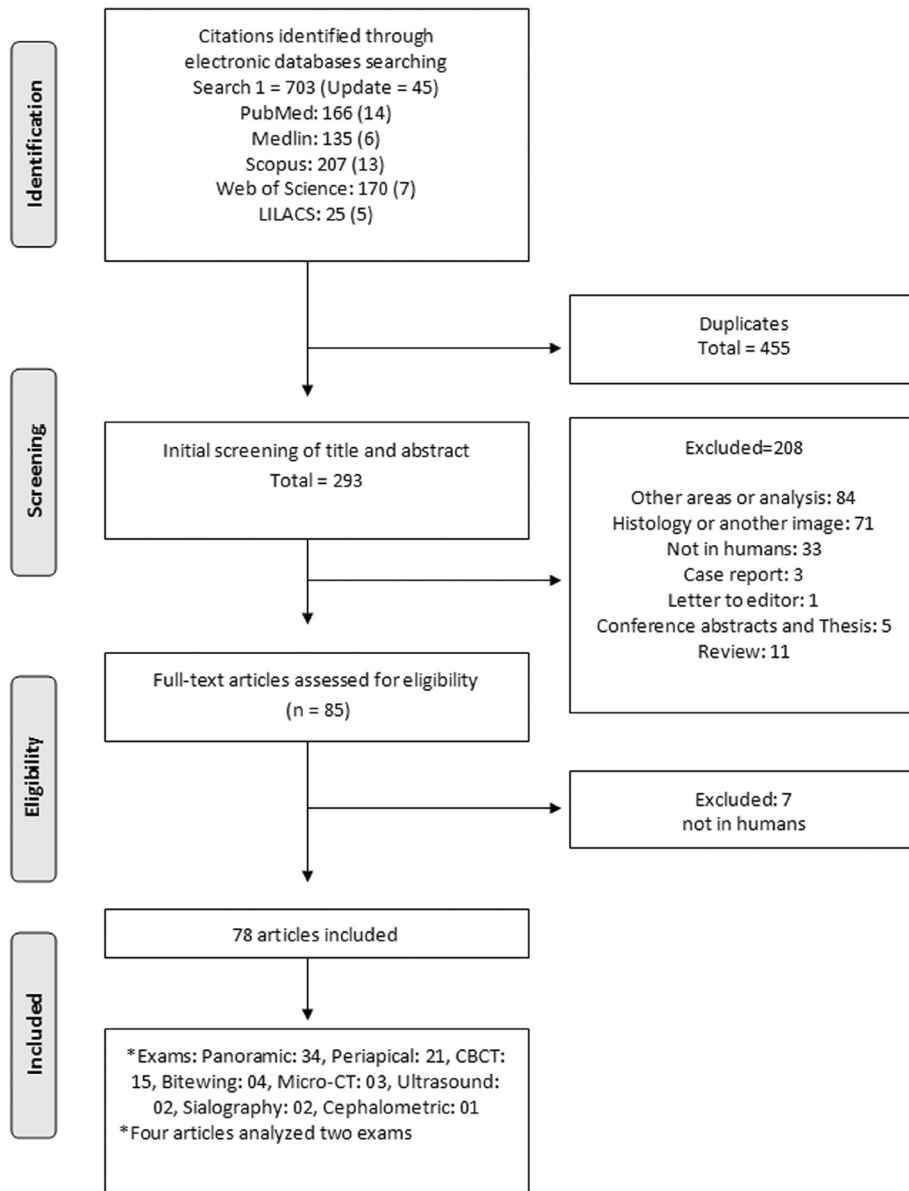
Figure 1 Flow diagram and results of the literature review in the PubMed database on the use of fractal analysis in dental images.

exams most used for FA were panoramic radiographs (34 articles),[10–12,15,16,19–47] periapical radiographs (21 articles),[2,5,45–63] and cone beam CT (CBCT) (15 articles).[1,64–77] Bitewing radiography,[63,78–80] micro-CT,[81–83] ultrasound,[84,85] sialography,[18,86] and lateral cephalometric radiography[87] were also found in this review (Figure 4).

The included studies showed different sample sizes. The smallest sample size was three individuals and the largest consisted of 1047 individuals. Most studies had 20–60 participants. Square ROIs of 64 × 64 pixels within trabecular bone were commonly used. FA using the box-counting method was conducted in 62 of the 78 articles included. Most studies ($n = 51$) used the public domain software *Image J* (https://imagej.nih.gov/ij/) for the application of the method, while 13 studies

used other types of software and 14 articles did not describe details about the software used for the analyses. Other aspects identified in the studies were a wide variety in the standardization of the images (Tiff, JPEG or Bitmap file format) and the lack of detailed information on image processing. 11 articles (7 studies with panoramic radiographs, 3 with periapical radiographs, and 1 with CBCT) carefully followed all the image processing stages proposed by White and Rudolph.[13] An example of the White and Rudolph[13] sequence of image preparation for the measurement of FD found in this review is detailed in Figures 5–7. In other studies, image processing varied in terms of the filters used and the manner of FD calculation.

Table 3 Main findings of the included articles according to the three most commons dental images assessed by fractal analyses

Exam	Panoramic radiograph	Periapical radiograph	CBCT
Number of studies	34	21	15
Year of publication	1995–2018	1998–2018	2011–2018
Type of studies (n)			
Accuracy	04	02	02
Cross-sectional studies	21	13	10
Follow-up	09	06	02
Clinical trial	-	-	01
Objective			
Bone mineral density	15	4	5
Diseases	8	5	4
Implant	7	4	1
Others	4	8	5
Sample size (n)	10–1047	9–600	3–165
ROI			
Shape			
Rectangular	16	08	01
Square	13	11	06
Anatomic	05	02	04
Others	-	-	04
Size (pixels)	10–300	23–400	20–128
Site			
Trabecular	29	21	15
Cortical	05	-	-
Method of calculation			
Software			
Image J	26	12	11
Others	04	04	02
Not described	04	05	02
Image format			
Tiff	07	01	-
Jpeg	05	01	02
Bitmap	02	05	-
Not informed	20	14	13
Box-counting	30	15	14
Others	04	06	01
FD values (Box-counting)	0.7768–2.7931	0.7768–1.8360	0.9100–2.4000
Main results (*n* studies)			
FD different between groups evaluated	23	12	08
FD similar between groups evaluated	05	05	03
FD showed correlation with other measures	05	02	02
FD had no correlation with other measures	-	01	01
Accuracy	>0.70	>0.75	>0.63

CBCT, cone beam computed tomography; FD, fractal dimension; N, number; ROI, region of interest.

Discussion

This scoping review illustrates the use of FA in dental images. We found studies on panoramic, periapical, bitewing and cephalometric radiographs and CBCT, as well as exams less commonly used in dentistry, such as micro-CT, ultrasound and sialography. The choice of the type of exam included in the method of each study was due to the availability of retrospective data or the advantages of each technique. Panoramic radiographic images were analyzed in different areas: trabecular mandibular bone, cortical mandibular bone, and condyle bone, while periapical radiographs and bitewing exams measured FD in bone crest, trabecular bone or periapical areas. Most studies evaluated periapical and panoramic radiographs, which are exams often used
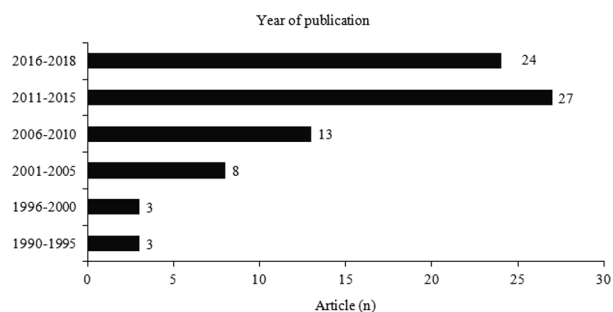
Year of publication

Figure 2 Distribution of the included articles on fractal analysis in dental images according to year of publication.

in clinical practice. More recently, FA on the CBCT images has been explored, but the number of studies is still limited. The main advantage of three-dimensional and high-resolution images is the feasibility of accurate evaluation of bone quality. Considering the low dose of radiation, minimized distortion and the possibility of real size images, cephalometric radiographs have advantages when compared to panoramic radiographs. But only one study, in this review, used this type of exam.[87]

In the conventional radiographic projections, panoramic, periapical, bitewing, and cephalometric images represent a set of structures that absorb the X-ray in a focal area, and generally result in overlaps, blurring and some degree of distortion of the bone structures. In contrast, CBCT and micro-CT images have a higher spatial resolution of hard tissue by means of multiplanar reconstructions that allow one to visualize structures in three dimensions with minimal distortion and without overlapping.[88] Voxel size may have an influence on FD values.[89] On the other hand, the acquisition of ultrasound images is entirely different from the acquisition of radiographs. A transducer dynamically captures the echoes generated by the reflections of the structures of the organism and transforms them into images.[90] In two studies included in this scoping review, FA was applied to ultrasound images for the evaluation of salivary glands in two-dimensional (2D) images.[84,85] The method of image acquisition is important in FA since the structures are measured in their projections of pixels of 2D images.
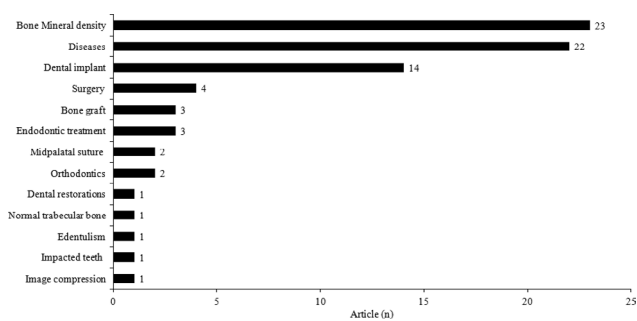

Figure 3 Distribution of the included articles on fractal analysis in dental images according to the objectives of the studies.
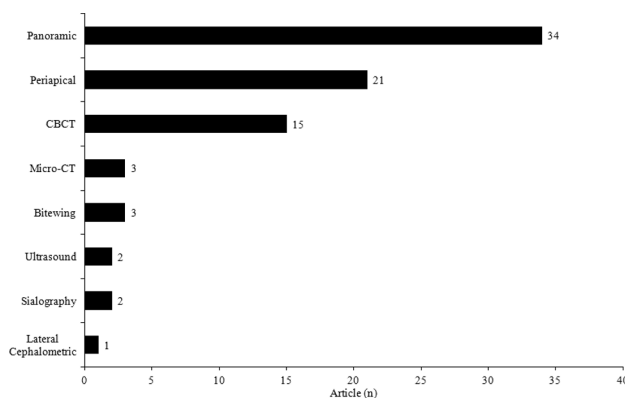

Figure 4 Distribution of the included articles according to the types of dental images that were evaluated by fractal analysis.

BMD investigation was the main aim of most of the studies included evaluating FA on panoramic and periapical radiographs. Studies have suggested that FD values have a positive correlation with BMD,[28,29] but differences between normal and osteoporotic groups have not been found elsewhere.[22,30,51] Some authors still observed increased FD values in groups with osteoporosis.[20,45] These authors have advocated that when there is a loss of BMD the trabecular structure becomes more complex and therefore, a greater number of fractals takes place. Controversies among studies may be associated with different methodologies,[14] but FA seems to be useful for the screening of patients with low BMD in dental images. Clinicians should not focus their analysis only on dental outcomes, because some characteristics of systemic alterations such as bone loss may be observed in dental exams.

Another benefit of using FA on panoramic radiographs is the primary stability of dental implants. Panoramic radiographs have been chosen because of their low radiation exposure and the need to perform exams pre- and post-implant.[15] The ROIs included mesial, distal and apical areas of different sizes. The follow-up period ranged from 6 months to 8 years.[10,19] A positive linear correlation between FD and implant stability quotient was observed.[15] High FD (range 1.34–2.659) values can predict the prognosis of osseointegration.[15,19,26,41] Although an increase in FD value has been

Figure 5 Example of selection of the region of interest in a periapical radiograph using *ImageJ* software. Periapical radiograph with a region of interest of 64 × 64 pixels in the trabecular bone.
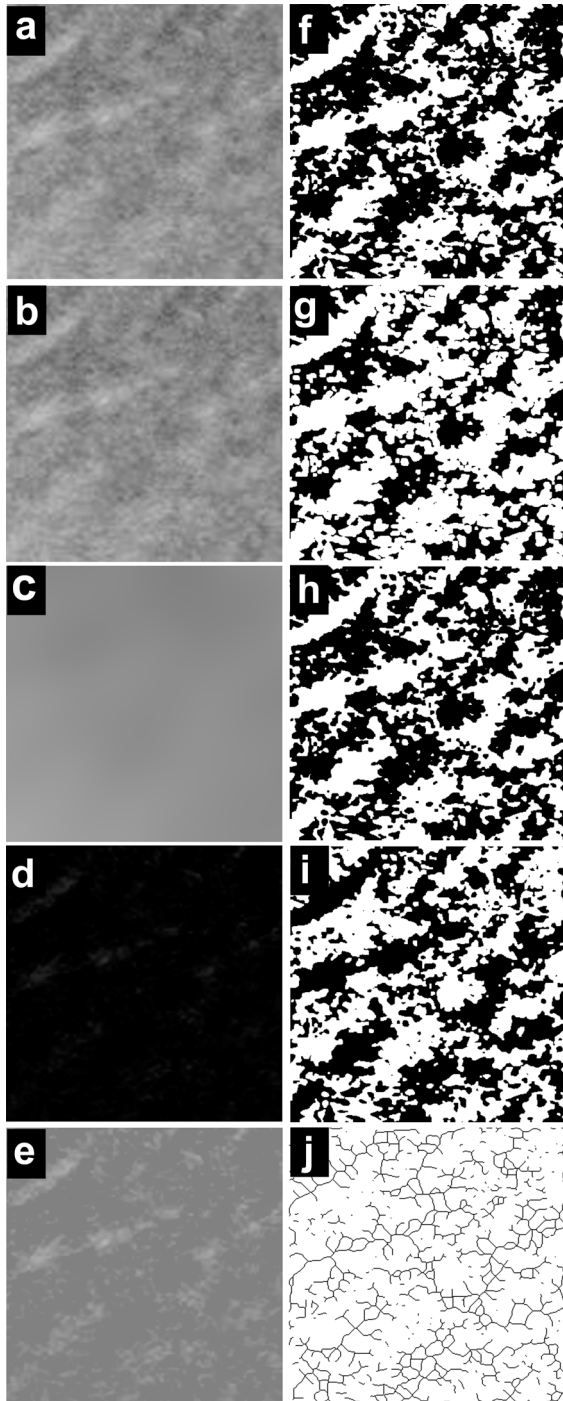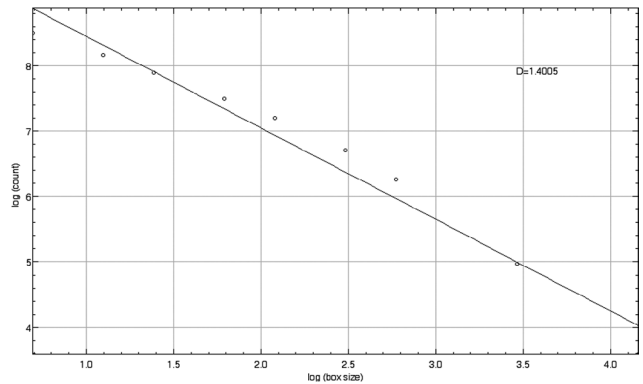
Figure 7 Graphic results of fractal analysis that provide a final value (D) called the fractal dimension (1.4513).

baseline and a 6 month follow-up. Conversely, the study of Onem et al[31] evaluated fractals on panoramic radiographs of patients with implants placed after 2–3 months and detected no difference between the area around the implant and the alveolar bone around a premolar tooth on the contralateral side. Osteointegration should be followed up with clinical and radiographic exams. In this respect, FA may assist the practitioner in the quantitative evaluation of radiographic images as a screening tool for primary stability of dental implants.

Systemic or local disorders such as imperfect osteogenesis,[38] chronic renal failure,[40] renal osteodystrophy,[46] sickle cell anaemia,[24] diabetes mellitus,[43] periodontitis,[2,48,54] hypodontia[27] and temporomandibular disorders[16] were also analyzed with FA in panoramic and/or periapical radiographs. Sjögren Syndrome and salivary gland tumors were observed by ultrasound[84,85] and sialography.[18,86] Most studies compared groups with and without disease. There was a difference among all the groups compared, except for diabetes mellitus[43] and hypodontia.[27] In general, FD has been used in several other dental specialties such as endodontics,[49,55,56] orthodontics[67] and oral and maxillofacial surgery.[5,21,25] Several studies can be conducted with FA to assess the patterns of bone complexity. A tool that calculates FD should be incorporated into the imaging program to facilitate access and allow the practitioner to further explore this methodology.

The advent of CBCT has brought great advances in dentistry. This diagnostic method uses three-dimensional imaging, a reliable tool for the evaluation and planning of dental implants,[65] investigation of sickle cell anaemia,[70] Type 2 diabetes mellitus,[74] temporomandibular osteoarthritis,[75] orthodontic tooth movement,[67] bone repair surgery,[76] impacted canines,[77] mid-palatal suture fusion,[71,73] and prediction of low BMD.[1,72] Similar to panoramic radiographs, FA on a CBCT slice can be helpful in the differentiation of groups of patients with low BMD.[1,69] However, other authors found no significant difference in FD values between postmenopausal females with and without osteoporosis. Instead, a significant negative correlation was observed between FD and

Figure 6 Sequence of image preparation for the measurement of fractal dimension, a: region of interest; b: duplication of the image of the region of interest; c: application of the gray filter (sigma 35); d: subtraction of the original image; e: resulting image with added grey-scale value of 128; f: binary image; g: eroded image; h: dilated image; i: inverted image, and j: skeletonized image from which the fractal value is obtained.

observed in most studies, Zeytinoğlu et al[10] stated otherwise. They found a reduction in FD values in the ROIs of 76 implants, with a significant difference between

lumbar spine BMD measured by DXA.[66,72] CBCT slices represent a small part of the real structure of trabecular bone, but the images saved in order to perform FA are of low resolution This suggests that the saved images are unsuitable for FA,[91] although more studies should be carried out to support this statement.

Micro-CT is considered to be the gold-standard for the evaluation of bone morphology, allowing the provider to thoroughly analyze structures of a few micrometers.[82,92] FD was also used on micro-CT images to evaluate the effect of porous titanium granules and bone graft materials in patients undergoing maxillary sinus lifting. No differences in FD values were found between micro-CTs of bone biopsies before grafting and after 6 months of follow-up.[83] In addition, FD on micro-CT was used to evaluate the relationship between systemic bone turnover and the microstructure of alveolar bone[81] and also to assess BMD at dental implant recipient sites.[82] Both studies observed positive and negative correlations of FD values and other parameters evaluated such as histo-morphometric analysis and radiographic bone density. Despite the high quality of micro-CT, few studies using this exam were identified. The high cost, dose of radiation and the necessity of a bone sample preclude the use of micro-CT.

The greatest advantage of FA is that it is a noninvasive technique. Robust results of evaluations of FD and other radiomorphometric parameters have been provided.[1,11,35,38] Accuracy studies have shown a satisfactory performance of FD values when compared to the test for BMD screening measured on panoramic radiographs.[11,28,39] However, FA is performed by means of the quantitative analysis of processed images. The images can be acquired from either analogic or digital equipment, which may change the FD values. Some authors have been actively engaged in studying image parameters of periapical and panoramic radiographs. The exposure time, resolution and compression of the images may interfere with FD results in 2D images, but this does not make their use unfeasible. Focus on the standardization of images is important.[9,33] An experimental study with CBCT images showed that, in contrast to exposure time, the variation of voxel size significantly changed FD values. Larger voxels appear to have lower FD values.[89] The standardization of these parameters would be important in order to obtain more robust results. Another recent analysis with dry human mandibles has suggested the use of panoramic radiographs instead of CBCT due to the low image resolution provided by the latter, in addition to the different radiation doses of the two exams.

In addition to *Image J*, other types of software were used to calculate FD, such as NRecon,[83] Scion Image[21,26] CTAn[70] and TAS Plus.[18,86] The box-counting method was the used method most frequently used for the calculation of FD, as previously observed in other reviews assessing FA.[6,14] Caliper, power spectrum and Rényi entropy methods are not often used.[20,27,34,78,79] A comparison of different algorithms for the calculation of FD identified different values for the same region. This is justified by the fact that each method has its own theoretical basis for acquisition. Therefore, one should standardize the method of evaluation, using a single method to compare the images and establishing an average value.[5]

The variety of shapes, sizes and sites of the ROIs in the included studies is remarkable. Overall, the trabecular bone region was the area predominantly chosen for the calculation of FD in the exams, although the mandibular bone cortex was included in the ROI in panoramic radiographs.[11,22,23,37,38] The difference in the architecture of trabecular and cortical regions may justify the lack of consensus among data on FD values. In periapical and panoramic radiographs, most authors agree that high FD values correspond to more complex trabecular bone, as generally observed in healthy patients.[2,28,30,35,54] However, these results were not observed by other authors,[20,46] as also demonstrated for CBCT images. Two recent studies have shown different results for FD values as a method to quantify BMD.[1,72] The images evaluated were similar in both studies (cross-sectional), but the size and site of the ROIs were different. Thus, studies with a standard size and site are encouraged.

The diversity of ROIs leads to the observation of differences in FD values. For trabecular bone, FD values calculated with box counting are generally between 1 and 2. Values closer to 1 represent simple structures with a lower number of fractals, while values closer to two indicate more complex bone structures.[15] The suggested value for the FD of a normal or healthy trabecular bone of the jaws is approximately 1.5 in periapical images,[59] but some studies with groups of healthy patients have detected a higher (1.74) or lower (1.05) FD value in the same exam.[2,54] Similar variations are observed in the results of FD on panoramic radiograph images.[11,12,22,37] In CBCT, FD values of 1.19 (osteoporosis) and 1.17 (healthy patients) were not significantly different. Different image parameters or differences of the ROI (size and site) in trabecular or cortical bone can justify such variations in values.

Noise and overlay removal images are treated in different manners in order to highlight the structure of trabecular bone. Authors[16,23,43,77] who followed the proposal of White and Rudolph[13] (crop of the ROI, duplication, Gaussian filter, subtraction, addition of 128 grey value, binarization, erosion, dilatation, inversion, and skeletonization) frequently found higher FD values than those who did not advocate image inversion prior to skeletonization.[10,29] The binary, skeletonized or outline image for counting fractals results in different FD values.[22,29,45] Reduction of noise with erosion and dilatation steps when performed three times can also result in elevated FD values in non-standardized periapical radiographs.[59] These image

processing steps interfere with the values found even when using a single fractal calculation method, such as box-counting.

Conclusion

The use of FA in Dentistry has increased substantially in the last years. Quantification of trabecular bone is required in several dental specialties, and the use of common dental images such as panoramic and periapical radiographs is preferred. Practitioners have at their disposal a free and easy handling system such as *Image J*, which allows them to analyze the image texture of their patients' exams. However, the reviewed studies did not present method standardization. This scoping review strongly recommends that future studies describe a standardized methodology used in their analyses, allowing comparison among them. The description should include details of image type, resolution, size, as well as shape, size and site

of the ROI. In CBCT images, information on voxel and slice thickness is also important. According to most included studies and their consistent results, the *Image J* software, the box-counting method and the White and Rudolph process image are suggested. Further studies are encouraged to improve clarification regarding the parameters that directly influence FA.

Funding

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