Critical Review

Cone-beam computed tomography cinematic rendering: clinical, teaching and research applications

Mike Reis BUENO[(a)]
Carlos ESTRELA[(b)]
José Mauro GRANJEIRO[(c)]
Matheus Rodrigues de Araújo ESTRELA[(d)]
Bruno Correa AZEVEDO[(e)]
Anibal DIOGENES[(f)]

[(a)]CROIF, Diagnostic Imaging Center, Cuiabá, MT, Brazil.

[(b)]Universidade Federal de Goiás - UFGO, School of Dentistry, Stomatologic Science Department, Goiânia, GO, Brazil.

[(c)]Instituto Nacional de Metrologia, Qualidade e Tecnologia – Inmetro, Duque de Caxias, RJ, Brazil.

[(d)]Universidade Evangélica de Anápolis - UniEvangéica, School of Medicine, Department of Anatomy, Anápolis, GO, Brazil.

[(e)]University of Louisville, School of Dentistry, Oral Radiology Department, Louisville, KY, USA.

[(f)]University of Texas Health at San Antonio, School of Dentistry, Endodontics Department, San Antonio, TX, USA.

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Corresponding Author:
Carlos Estrela
E-mail: estrela3@terra.com.br

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Abstract: Cone-beam computed tomography (CBCT) is an essential imaging method that increases the accuracy of diagnoses, planning and follow-up of endodontic complex cases. Image postprocessing and subsequent visualization relies on software for three-dimensional navigation, and application of indexation tools to provide clinically useful information according to a set of volumetric data. Image postprocessing has a crucial impact on diagnostic quality and various techniques have been employed on computed tomography (CT) and magnetic resonance imaging (MRI) data sets. These include: multiplanar reformations (MPR), maximum intensity projection (MIP) and volume rendering (VR). A recent advance in 3D data visualization is the new cinematic rendering reconstruction method, a technique that generates photorealistic 3D images from conventional CT and MRI data. This review discusses the importance of CBCT cinematic rendering for clinical decision-making, teaching, and research in Endodontics, and a presents series of cases that illustrate the diagnostic value of 3D cinematic rendering in clinical care.

Keywords: Cone-Beam Computed Tomography; Endodontics; Diagnosis.

Introduction

Recent advances in information technologies have changed human knowledge and, particularly, Dentistry.[1,2,3]

Cone-beam computed tomography (CBCT) constitutes an advancing imaging method, essential part of contemporary Endodontics, resulting in increased accuracy of diagnoses, planning and follow-up.[4,5,6,7,8] Dental CBCT scans provide visualization of digitized images of structures of an anatomical section of the maxilla and mandible in several planes.[2,3,4,9] Different CBCT scanners feature a characteristic sensor type, field of view (FOV) and resolution, as well as specific native software for their operation. Therefore, some devices may be more suitable for the acquisition of high-resolution images, whereas others should be the choice when a larger FOV is required.[10,11,12,13]

CT images have a three-dimensional volume, as a depth dimension (z) is added to form a cube, called voxel. Importantly, the voxel size in CBCT images is isotropic, that is, all sides have the same dimension. Usually, the smaller the voxel, the sharper the image tends to be.[6] However, the voxel size is not always indicative of resolution as other factors need to be considered such as noise to signal ratio. Because of these differences, some scanners are more suitable for specialties that require high-resolution images, and others, for specialties that have to scan larger area and volumes.[1,6]

Scarfe, Molteni and Mozzo[14] studied the reconstruction of a volume data set and found that primary images captured in a CBCT scan are a sequence of 2D images, known as projection data, raw data, basis projection or basis frames. Once acquired, projection data are mathematically processed by the scanner native software to generate a volumetric data set. There may be from 100 to over a 1,000 individual projection frames, each with over half a million pixels, and a 12- to 16-bit value assigned to each pixel. Hence, data reconstruction is computationally complex and the resulting volumetric data set is a contiguous collection of cuboidal data points within a FOV, which has two properties: a 3D location, which is a spatial coordinate, and an intensity value associated with the radiographic density at that coordinate. As stated previously, each discrete unit in the volumetric data, or points cloud, is called a voxel (volumetric element), the 3D equivalent of the pixel (picture element) in a 2D image.[14]

The same data set is used for 2D and 3D images, and one of the points that differentiates 3D images is transparency control. A CBCT image that is adequate for analysis should be both acquired and reconstructed carefully.[6] In image reconstruction, primary data are reconstructed to generate a 3D volumetric data set and to facilitate visual display of images when using several display techniques, whether 2D, 3D or others.[14,15] Volume parameters should undergo basic adjustments (volume editing) in postprocessing to make sure they are appropriate for the recognition of fundamental structures in the image. The main adjustments are brightness, contrast, noise management and sharpness control. They depend on each other and on the purpose for which the imaging study was requested.[1] Although there has been great advanced in image processing for the 2D representations of the x, y and z slices, far less has been done for 3D rendering of the scanned structures that could convey valuable clinical information.[1]

Indeed, image visualization relies heavily on the software capacity to post-process the data set adequately, and the use of predetermined tools for the quantitative (i.e. measurements) and qualitative (*i.e.* image filters) assessment to provide clinically useful information for diagnoses, planning and follow-up.[1,14,15,16,17] Notably, various techniques have been proposed for image postprocessing when using computed tomography (CT) and magnetic resonance imaging (MRI) data sets such as maximum intensity projection (MIP), volume rendering (VR) and multiplanar reformations (MPR).[16] A CBCT scan volume is reformatted in three planes (X, Y and Z) for MPR, representing the most commonly used postprocessing since allows the operator to change the spatial position of these planes according to the needs of visualization and interpretation. In addition, plane inclination and thickness, brightness, contrast and sharpness may also be changed.

Although image visualization based on MPR seems to be the most common for diagnostic images, it has some disadvantages in endodontics. Both non-surgical and surgical endodontic procedures rely on understanding precise anatomical structures in 3D often without direct visualization. Astute clinicians carefully study the 3 planes (x, y and z) through the dynamic navigation of the volume to create a mental 3D image of tooth and surrounding anatomical structures.

However, appropriate 3D rendering has the potential to favor faster understanding of spatial anatomical structures, by providing an already reconstructed anatomically accurate 3D image.[18]

Volume rendering is another image postprocessing technique. For visualization, all acquired volumetric data are processed, resulting in a 3D model that can be manipulated and customized in real-time to display anatomic details from various perspectives. This technique, that is already present as a feature in many of the CBCT scanner native software, is simple to compute, but neglects complex light paths, such as scattering and light extinction, which results in images with a more artificial appearance that is often granular with present of artifacts.[19] Dalrymple et al.[17] found that volume rendering assigns opacity values on a full spectrum from 0% to 100% (total transparency to total opacity) along an artificial line of sight projection using a variety of computational techniques. This method combines the use of opacity values and lighting effects that may be used to evaluate spatial relationships between structures. In volume-rendered reconstructions, compared with classic CT reformatting, the all-encompassing data analysis of volume-rendered images creates an accurate 3D representation of target tissues. Using this process, larger volumes may be visualized on a single image, and distant structures and their spatial relations may be simultaneously evaluated.[20]

Cinematic rendering, a novel reconstruction method, is an advance in 3D data visualization. This new method has a potential for greater diagnostic accuracy because of an improved 3D display of anatomical details resulting from its exclusive lighting mode.[20,21,22,23,24,25,26] Cinematic rendering is a 3D reconstruction technique that generates more photorealistic 3D images from conventional CT and MRI data sets. Its development has been encouraged by the animation movie industry (Pixar Animation Studios), which has created highly realistic-looking characters. Hence, the name: Cinematic Rendering.[20] It follows the steps used for volume rendering to determine color and opacity: gray values in each voxel of the original image are mapped to a color and opacity value. The algorithm used in cinematic rendering is based on path-tracing methods and the illumination modeling. Thus, this technique simulates real-life physical propagation of light and generates highly photorealistic 3D images based on data acquired.[16,20,25,26] This photorealistic quality depends on high dynamic range rendering lightmaps used to create a natural lighting environment by simulating realistic lighting effects from real-world environments.[20] According to Dappa et al.,[25] cinematic rendering uses the same necessary steps as conventional volume rendering techniques, that is, the axial thin-slice, isotropic voxel data set is stacked to create the 3D volume. Each voxel of the data set is assigned a color and transparency value based on its relative tissue composition. Then light is projected through the volume to create a 3D image. Because cinematic rendering is a physical simulation of light diffusion, effects, such as environmental influences, shadowing, refraction, ambient occlusion, dispersion and soft shadows, may result in a high dynamic range rendering. One of the most important characteristics of cinematic rendering is that it has postprocessing tools that may be used to generate, manipulate, and refine the final image.[20]

In addition to its application to generate images for diagnosis and clinical decision-making, cinematic rendering has innovative strategies that may benefit the teaching of human anatomy,[27] dental anatomy and has tremendous application in endodontic research. Undoubtedly, imaging studies may provide valuable information for the improvement of clinical practice. However, knowledge about cinematic rendering for the photorealistic visualization of CBCT images in Endodontics remains incomplete. A better understanding of this technique may positively affect the value of informative details. This review discusses the importance of CBCT cinematic rendering for clinical decision-making, teaching, and research in Dentistry and a series of cases that illustrates the diagnostic value of cinematic rendering is presented.

Methodology

This study conducted a search of MEDLINE, Scopus, Web of Science and Scielo using a search strategy with the terms (cinematic rendering AND computed tomography) and no language or publication date restriction. The studies retrieved were classified according to use of cone-beam computed tomography and use of 3D visualization OR cinematic rendering as an educational tool. Selection criteria were: a) use of CT as an imaging method; and b) cinematic rendering. Abstracts and letters were excluded.

Studies were selected in two rounds by two authors. In the first round, titles and abstracts were analyzed for selection. Studies were included for the next step even if only one reviewer selected it to ensure the inclusion of as many studies as possible. After removing duplicate results, the full text of the studies selected according to inclusion criteria were reviewed, and the final selection was defined. Differences in study selection were resolved by consensus after the reviewers discussed each study. Bibliometric networks were constructed using the VOSviewer software (v. 1.6.15, CWTS, Leiden University, Netherlands).[28]

Cinematic rendering images of CBCT scans were presented in a series of five clinical cases using a novel CBCT software[1] (e-Vol DX, CDT Software; São José dos Campos, Brazil) and a photorealistic tool that uses AI-related algorithms.

In all endodontics cases presented here, CBCT scans were acquired using PreXion 3D scanner (Prexion 3d Inc., San Mateo, USA), with the protocol: FOV - 56mm x 52mm; voxel - 0.108mm; rotation - 360°; exposure time - 37 s; bits - 13; tube voltage: 90 kV; and tube current: 4 mA. CBCT scans were reconstructed using the proprietary software native to the scanner. The volume was exported as an axial multi DICOM series and imported into a novel software (e-Vol DX, CDT Software; São José dos Campos, Brazil) running on a PC workstation equipped with an Intel i7-7700K processor, 4.20 Ghz (Intel Corp., Santa Clara, USA), NVIDIA GeForce GTX 1070 video card (NVIDIA Corporation, Santa Clara, USA), Dell P2719H monitor at a resolution of 1920X1080 pixels (Dell Technologies Inc., Texas, USA) and Windows 10 Pro (Microsoft Corp., Redmond, WA); and i-CAT Classic CBCT scanner (Imaging Sciences International, Hatfield, USA), with the protocol: FOV - 160mm x 130mm; voxel - 0.25mm; rotation - 360°; exposure time - 40s; bits - 14; tube voltage: 120kV; tube current - 3-7 mA.

The original CBCT scans were visualized using the scanner's original software package. The volume was exported in a multifile DICOM format and reconstructed using the e-Vol DX software. Initially, the areas of interest ware analyzed using a pattern determined in the global analysis of all the images of the oral and maxillofacial complex previously acquired.

Results

The initial literature search retrieved 144 studies: 54 from PubMed, 58 from Scopus, 32 from Web of Science, and zero from Scielo (Figure 1). After removing 85 duplicates and one study that did not meet inclusion criteria, 58 studies were included in the review.

The VOSviewer Software used in the full counting mode identified 14 terms with at least one occurrence (threshold) of it in titles and abstracts. These terms were: focal liver mass and cinematic rendering, evaluation, enhancement pattern, visualization, rendering technique, pretreatment planning, potential application, focal liver mass characterization, global

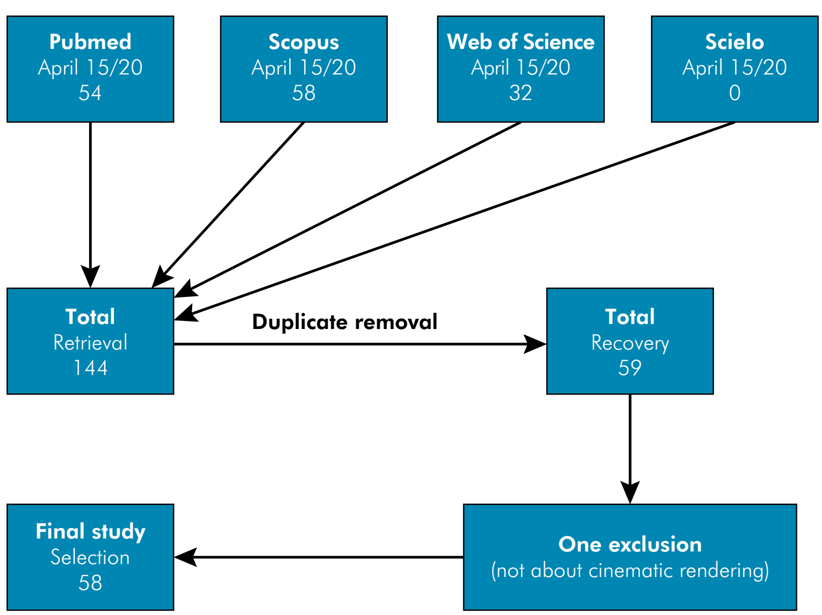

Figure 1. Study selection design.

disease burden, internal architecture, local tumor extension, new lighting model, and photorealistic image. From this search, 2 of the most recurrent authors were Elliot K. Fishman and Steven P. Rowe, both from The Russell H. Morgan Department of Radiology and Radiological Science, Johns Hopkins University, USA. The total number of Scopus citations of studies on cinematic rendering and CT authored by Fishman was 209. His first paper on this topic was published in 2017.

Discussion

Few studies in the dental literature have investigated the acquisition of CBCT images and their analysis using cinematic rendering reconstruction techniques and the generation of photorealistic 3D images. This study used specific keywords - cinematic rendering AND computed tomography - and reviewed studies published in relevant databases - MEDLINE, Scopus, Web of Science and Scielo - without any language or publication date restrictions (Figure 1). The Table summary the selected references regarding the application reported of cinematic rendering reconstruction techniques. Of the 58 studies included in the study,[20,23,26,29,31,32,33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,66,66,67,68,69,70,71,72,73,74,75,76,77,78,79,80,81,82,83,84,85,86] three were associated with cinematic rendering and CBCT, but one study demonstrated the application of cinematic rendering (CR) for a photorealistic 3D visualization of oral and maxillofacial structures. In that study, Stadlinger et al.[29] published a technical note about the uses of CT and CBCT data for cinematic rendering illustrations of maxillofacial anatomy, adding a special focus on pathologies, fractures, and tooth structures. The authors concluded that cinematic rendering generates photorealistic 3D reconstructions of high-density structures and abnormal findings, and that it has potential applications in maxillofacial bone and tooth imaging.

In the clinical cases presented here, the use of the e-Vol DX cinematic rendering tool increased the amount of information provided because of improved image quality and natural visualization of anatomic structures. In case 1 (Figure 2), lateral maxillary incisor luxation and alveolar ridge fracture was visualized in sharp photorealistic 3D images of naturally well-defined dental and bone structures. This ensured the adequate repositioning of the tooth in the alveolus and of the bone plate. In case 2

Table. Summary of the selected references regarding the application reported.

Clinical diagnostic imaging	Application		
	Reference	Education (Training or teaching)	Reference
Aorta	34, 39, 72	General	31, 33, 41, 45, 46, 52, 60, 68, 79
Aneurism/mycotic	64	Tumors	40
Angiography	48, 49, 76	Autopsy	42
Arthritis	78		
Bowel	59,61		
Colitis	83		
Fetal anatomy	65		
Heart, coronary disease	54, 55, 63, 66, 73, 74		
Liver	38		
Maxillofacial	43, 44, 77		
Orthopedics	31, 43, 50, 53, 81		
Pancreas	56		
Soft tissues	37, 51, 70		
Tumors	35, 36, 40, 47, 51, 57, 58, 62, 67, 69, 71, 75, 80, 82		

(Figure 3), 3D cinematic rendering provided useful information for the evaluation of the bone depression in relation to the nasal fossa, data that was important to make a decision about the extent of the surgical intervention. In case 3 (Figure 4), the presence of a middle mesial canal, that is, a third canal between the buccal and lingual canals of the mesial root, was accurately evaluated using the e-Vol DX software and its photorealistic 3D cinematic rendering tool. In case 4 (Figure 5), the presence of a middle mesial foramen of the mesial root of mandibular first molar with root canal retreatment and secondary infection seemed to be not as accurate in 2D image compared to 3D cinematic rendering. In clinical case 5 (Figure 6), the shape and position of fracture fragments could be better analyzed because of 3D cinematic rendering, and a better clinical decision was made about whether bone fragments should be removed

Figure 2. Case 1 (A-C). A 36-year-old woman was referred to a private oral and maxillofacial radiology clinic (CROIF, Cuiabá, Brazil) for imaging studies to assess trauma that resulted in fracture of the crown of maxillary incisors. Clinical examination revealed upper lip edema. Her medical history was negative for any comorbidities. A CBCT scan showed fracture of the crowns of maxillary incisors. In addition to that, her diagnosis included lateral and partially intrusive luxation of central incisors and fracture of the alveolar ridge. The e-Vol DX software and its advanced photorealistic 3D rendering tool (C) provided elements for a better analysis of fragment shapes and the position of the alveolar fracture and supported the decision about repositioning of the tooth and the fragments.

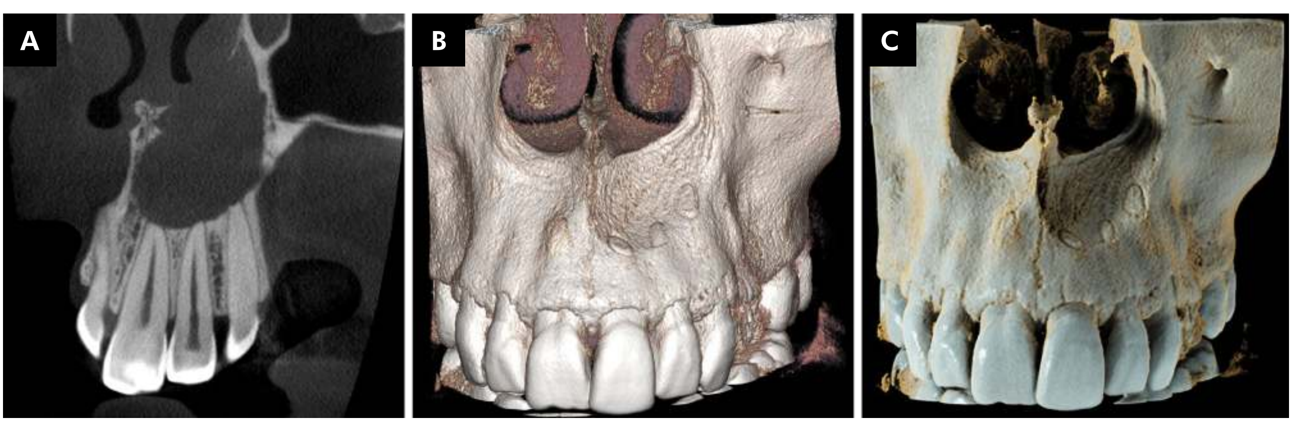

Figure 3. Case 2 (A-C). A 40-year-old woman was referred to a private oral and maxillofacial radiology clinic (CROIF, Cuiabá, Brazil) for imaging studies to assess a volumetric increase of the apical region of left maxillary incisors and canine. Her medical history was negative for any comorbidities. CBCT scans showed bone depression above the apex of teeth #21, #22 and #23, as well as resorption in the apical region of the same teeth (A-C). A soft tissue lesion in the region was removed, and histological analysis of the specimen revealed a nasolabial cyst. The e-Vol DX software and its advanced photorealistic 3D rendering tool (C) provided information for the evaluation of the bone depression in relation to the nasal fossa, data that was important to make a decision about the extent of the surgical intervention.

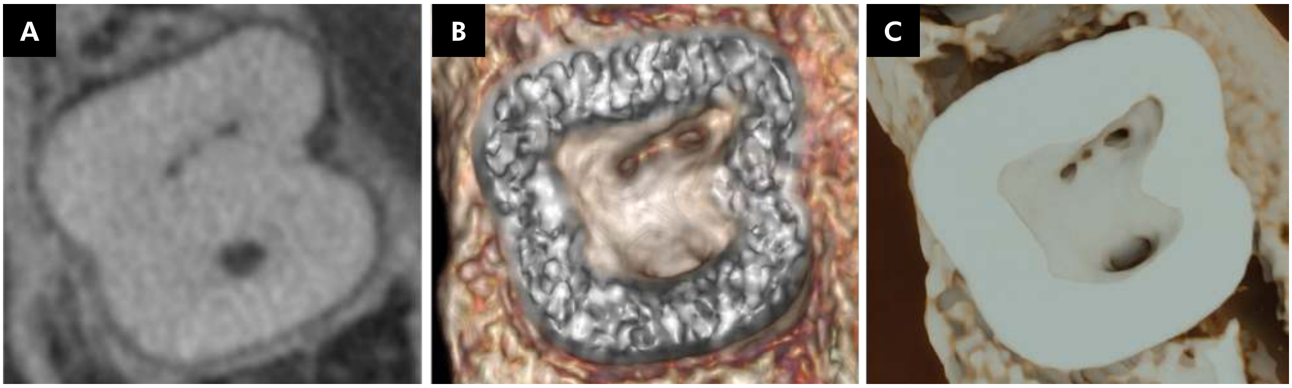

Figure 4. Case 3 (A-C). A 35-year-old woman was referred to a private oral and maxillofacial radiology clinic (CROIF, Cuiabá, Brazil) for imaging studies to elucidate the origin of pain in the region of teeth # 36 and #37, as well as the anatomy of the root canals of the same teeth. CBCT scans showed a wide distal canal and narrow mesial canals in tooth #37, as well as an unclear finding between these mesial canals. The e-Vol DX software and its advanced photorealistic 3D rendering tool (C) provided a better view and confirmed the presence of a middle-mesial canal, that is, a third canal between the buccal and lingual canals of the mesial root.

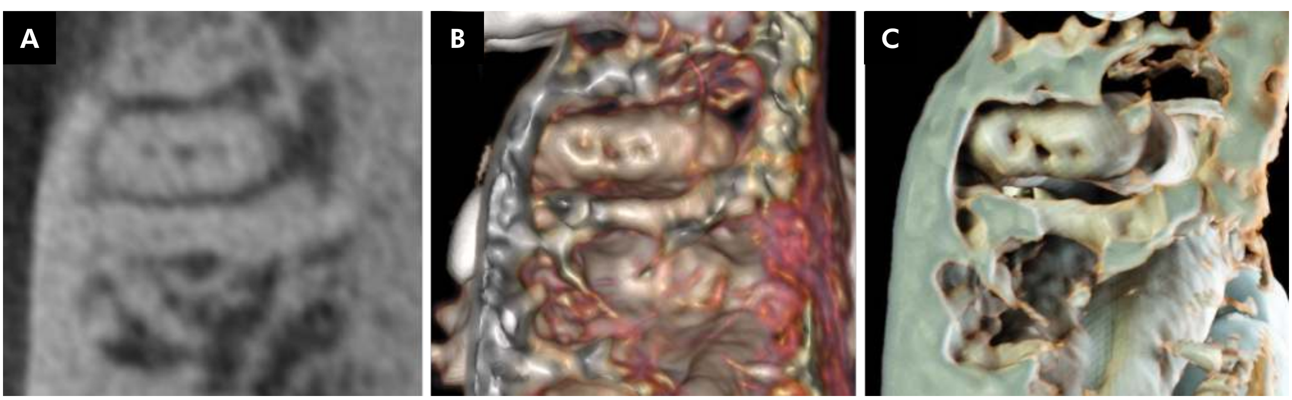

Figure 5. Case 4 (A-C). CBCT scans showed a tooth #46 with root canal retreatment, secondary infection and widening of the periodontal space. The patient complained of sensitivity in this region. In the CBCT scan navigation it was possible to identify 3 apical foramens in the mesial root. The photorealistic 3D rendering tool (C) provided a better view that the conventional volumetric rendering and confirmed the presence of a middle-mesial foramen with a larger dimension, that appeared in the apical third of the mesial root.

or not. The photorealistic cinematic rendering of maxillofacial structures provided powerful details for the investigation, which certainly increased diagnostic accuracy and had an impact on clinical decision-making. High dynamic range resulting from the natural photorealistic quality of images positively affected the visualization of details used for the analysis of shape and depth. Moreover, image navigation using a specific light source might reveal essential details for a diagnosis and the adoption of a certain treatment plan.

Other studies have reached similar conclusions about cinematic rendering.[16,20,21,22,23,24,25,29]

During the diagnosis process and therapeutic decision making, it is essential to have accurate imaging exams, since they are able to offer the greatest number of correct information. The inadequate acquisition and processing of CBCT scans may lead to misdiagnosis. This improved imaging modality has strong potential to be employed in machine learning and the development of artificial intelligence tool to aid in diagnosis and treatment planning in real-time.

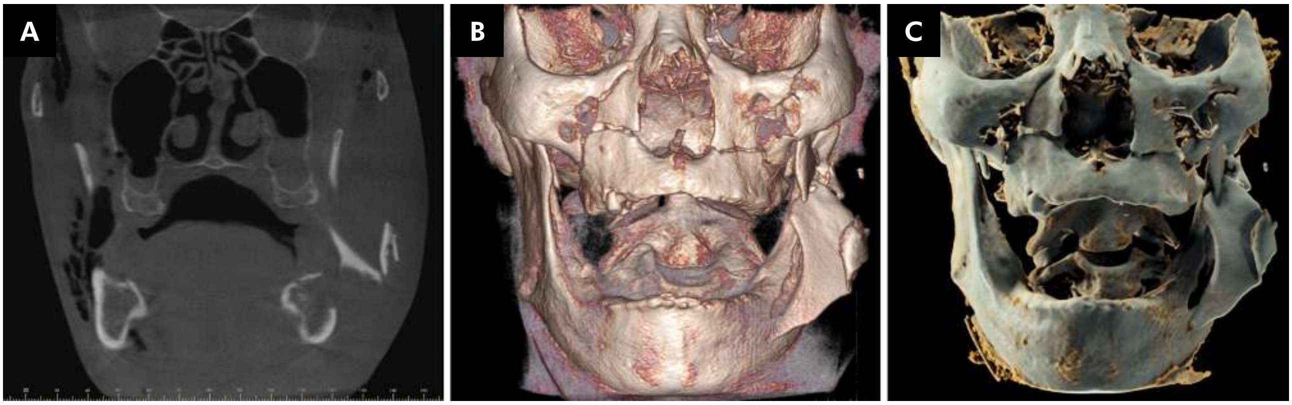

Figure 6. Case 5 (A-C). A 58-year-old man was referred to a private oral and maxillofacial radiology clinic (CROIF, Cuiabá, Brazil) for imaging studies to assess facial trauma after a serious motor-vehicle accident. Clinical examination revealed facial trauma and trismus. CBCT scan showed multiple facial fractures (A-C). The diagnosis was multiple facial fractures involving the mandible, maxilla, nasal fossa, floor of the orbit and zygomatic arch. The e-Vol DX software and its advanced 3D cinematic rendering tool (C) provided elements for a better analysis of fragment shapes and location and supported the decision of whether fragments should be kept or removed, as well as the planning of bone fragment repositioning during surgical facial reconstruction.

In recent studies,[86,87] the CBCT e-Vol DX software cinematic rendering tool was used, which made a big difference by offering high quality images with root canal shapes and apical foramen. The experience, knowledge and training of the operator with the software is essential to achieve the best results in post-processing and interpretation of images, which enables more predictable outcomes.

Recent medical advances[21,22,25] have demonstrated the relevance of cinematic rendering as a resource for imaging studies used in making diagnoses and clinical decisions in several medical specialties.[20,21,22,23,24,25,26] A new method of cinematic rendering has been developed as and advance in the visualization of 3D data sets. One of the features of this advanced tool, which results from its exclusive illumination options, is the potential to achieve greater diagnostic precision and generate an improved display of 3D data and of anatomic details.[20,21,22,23,24,25,26] Its high dynamic range lighting ensures that the natural illumination of the rendered data[30] generates a more realistic and visually attractive 3D image, which affects and improves the perception of depth and shape.[20,21,22,23,24,25,29] Comaniciu et al.[18] analyzed the potential of contemporary technological resources that extrapolate their impact to improve the quality of medical imaging. Techniques such as movie rendering help increase the sensitivity and specificity of imaging tests and improve the visibility and identification of any abnormal findings. Understanding images will simplify the interpretation of images, increase reading speed and, at the same time, introduce more reproducibility into the system. Patient-specific computational modeling opens the door to a new generation of clinical decision-making support systems that not only integrate and analyze data from different sources, but also provide models of patient anatomy and function and, therefore, improve predictive power.

The use of a more sophisticate CBCT software[1] (e-Vol DX) results in better image quality and the generation of more information to support diagnoses, planning and the management of endodontic complex cases. This imaging method generates high-resolution images because of submillimeter voxel sizes, dynamic multiplane imaging navigation, choice of volume parameters, such as slice thickness and slice intervals, and data correction by applying imaging filters and manipulating brightness and contrast. Several features make this CBCT software potentially applicable in clinical environments. It is compatible with all current CBCT scanners and may export files using DICOM data, which offer a comprehensive brightness and contrast library. Moreover, slice thickness and sharpening may be customized, and its advanced noise reduction algorithm improves image quality. It also features filters for preset imaging and dedicated volume rendering, which may enlarge images over 1,000x in 3D reconstructions without loss of resolution. Its imaging parameters may be automatically customized for standardization and several research purposes. Its capture screen resolution is 192 dpi, with a 384 dpi option. This photorealistic cinematic rendering tool, which uses Artificial Intelligence-related algorithms, has been developed for reconstructions.

New perceptions with the incorporation of technologies have improved the prediction of results and prognoses in several areas of health, such as in imaging exams. The use of artificial intelligence through new and revolutionary software, as well as the potential for improving data in the learning process with machine learning has determined promising prospects in all areas of health. Machine learning is on the way to revolutionizing the future in healthcare, with the ability to transform data into knowledge. Obermeyer and Emanuel[88] describes three potentials associated with this model: machine learning will dramatically improve the prognosis; machine learning will shift much of the work of radiologists and anatomical pathologists, since massive imaging data sets, combined with recent advances in computer vision, will provide rapid improvements in machine performance and accuracy; consequently, machine learning will improve diagnostic accuracy. In this way, Lakhani et al.[89] highlighted that machine learning has the potential to improve patient care, and particularly for radiologists. Special attention in the machine learning space has focused on the ability of machines to classify image findings, however, there are other useful applications of machine learning that will improve efficiency and utilization of radiology practices.

Another important use of the cinematic rendering tool is its application in teaching and learning of human anatomy. Anatomic structures, their location, morphological variation, spatial relations, shapes, depths and connections with other structure of interest may be explored using a multiplane navigation system. The development and use of new teaching technologies has been demanded as part of new educational strategies, which do not, however, exclude other models.[27,84-86]

The essential benefits to be added to treatment protocols by advances in imaging techniques should be better understood. CBCT cinematic rendering provides 3D images of the anatomical structure that is more detailed and comprehensive than conventional 2D images (Video 1). Video 1 illustrates a CBCT scan of a maxillary first molar with apical periodontitis and a coronary chamber with two root canals in the mesiobuccal root. A better quality and number of information can be viewed with cinematic rendering. Thus, a greater number of details may be useful and more enlightening in the differential diagnosis of periapical diseases, anatomical structure, planning, clinical decision-making and teaching. The power of information that may be acquired when using photorealistic cinematic rendering visualization is enormous and should be better investigated. Further studies should compare the CBCT e-Vol DX software and other software packages used with different scanners.

Conclusions

A cinematic rendering reconstruction technique that generates photorealistic 3D images is promising and has a good potential for application in clinical practice, research and teaching in Oral and Maxillofacial Radiology and Endodontics.

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The Video can be viewed in the online version of this article [https://doi.org/10.1590/1807-3107bor-2021.vol35.0024].