Dentomaxillofacial Radiology (2021) 50, 20200159

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TECHNICAL REPORT

Applying synthetic radiography to intraoral tomosynthesis: a step towards achieving 3D imaging in the dental clinic

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Objectives: A practical approach to three-dimensional (3D) intraoral imaging would have many potential applications in clinical dentistry. *Stationary* intraoral tomosynthesis (sIOT) is an experimental 3D imaging technology that holds promise. The purpose of this study was to explore *synthetic* radiography as a tool to improve the clinical utility of the images generated by an sIOT scan.
Methods: Extracted tooth specimens containing either caries adjacent to restorations (CAR) or vertical root fractures (VRF) were imaged by sIOT and standard dental radiography devices. Qualitative assessments were used to compare the conspicuity of these pathologies in the standard radiographs and in a set of multi-view *synthetic* radiographs generated from the information collected by sIOT.
Results: The sIOT-based *synthetic* 2D radiographs contained less artefact than the image slices in the reconstructed 3D stack, which is the conventional approach to displaying information from a tomosynthesis scan. As a single sIOT scan can be used to generate *synthetic* radiographs from multiple viewing angles, the interproximal space was less likely to be obscured in the *synthetic* images compared to the standard radiograph. Additionally, the multi-view *synthetic* radiographs can potentially improve the display of CAR and VRFs as compared to a single standard radiograph.
Conclusions: This preliminary experience combining *synthetic* radiography and sIOT in extracted tooth models is encouraging and supports the ongoing study of this promising approach to 3D intraoral imaging with many potential applications.
Dentomaxillofacial Radiology (2021) **50**, 20200159. doi: 10.1259/dmfr.20200159

Cite this article as: Puett C, Inscoe CR, Hilton RL, Regan Anderson MW, Perrone L, Puett S, et al. Applying synthetic radiography to intraoral tomosynthesis: a step towards achieving 3D imaging in the dental clinic. *Dentomaxillofac Radiol* 2021; **50**: 20200159.

Keywords: tomosynthesis; radiography; carbon nanotubes; dental caries; tooth fractures

Introduction

X-ray imaging is used extensively in clinical dentistry for screening and diagnosis of common oral conditions. Two-dimensional (2D) images, however, inherently limit visibility due to the superimposition of tissues. Three-dimensional (3D) imaging has demonstrated value when applied to many different clinical situations,[1–9] using available technologies such as CBCT and tuned-aperture CT (TACT). But these conventional 3D imaging techniques have not been demonstrated to be appropriate or practical for diagnosing common dental conditions.[10,11] *Stationary* intraoral tomosynthesis (sIOT) is an experimental technology that may provide a viable 3D imaging option for the busy dental clinic.[12] By utilizing a compact array of carbon nanotube (CNT)-enabled X-ray sources, the sIOT device itself was designed to

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Received 14 April 2020; revised 02 June 2020; accepted 03 June 2020

mimic the standard intraoral X-ray equipment currently in use. Also, since the imaging geometry is stationary, no additional time or training is needed to perform the scan. Previous *ex vivo* work has demonstrated the potential value of sIOT to improve the diagnosis of common dental conditions, since it generates images with reduced tooth overlap[12,13] and thereby improves the detection of interproximal caries, as compared to standard 2D intraoral radiography.[12,14] Based on these findings, a clinical study is underway to evaluate sIOT for the detection of interproximal caries in human subjects (ClinicalTrials.gov Identifier: NCT02873585).

However, to be of value for general dentistry, the images generated by the sIOT scan must be efficient to interpret and familiar to the practising clinician. Similar to other 3D imaging technologies, the information obtained during a tomosynthesis study is most commonly displayed as a stack of image slices. This 3D stack of images is "reconstructed" by computer programs from the 2D information present in the multiple projection views collected at the time of the study. The reader scrolls through the stack of image slices to appreciate anatomical and pathological changes through depth. In this way, features of interest can be separated from overlapping structures that would otherwise obscure them in a single 2D image. Typically, the reconstructed image slices step 0.5 mm through depth, such that an sIOT scan can produce an image stack containing more than 40 images. Reviewing all of these images takes time, and since the reconstructed images display information differently than the standard 2D radiograph, training and experience are needed for accurate interpretation. Additionally, the reconstructed image slices often contain artefact. Artefact is most prominent adjacent to metal and radiopaque restorative materials. As a result, assessing subtle pathology in these critical boundary regions can be problematic.[15,16]

In contrast to previous work with sIOT, this study sought to address the limitations in the presentation of information from an sIOT study through the use of *synthetic* radiography. *Synthetic* radiographs are 2D images that are generated from the information in the reconstructed 3D image stack using a chain of computer-processing steps. These steps provide opportunities to adjust the appearance of the *synthetic* image, allowing for artefact removal, replicating the appearance of standard radiographs, and even enhancing pathologic features. As such, *synthetic* radiography has the potential to combine the efficiency and familiarity of 2D imaging with the improved diagnostic accuracy of 3D imaging.

The idea to explore *synthetic* radiography with dental imaging was inspired by our experience with *synthetic* mammography applied to *stationary* digital breast tomosynthesis (sDBT).[17] Although the *synthetic* mammogram is now recognized as a valuable clinical tool,[18–21] the application of *synthetic* radiography to dental imaging is new and has required the development of unique processing approaches to handle the quite different and complex anatomical environment of the oral cavity.

The purpose of this study was therefore to assess the potential utility of presenting sIOT information as *synthetic* radiographs, using caries adjacent to restorations (CAR) and vertical root fractures (VRF) present in extracted teeth as model systems. These two pathologies were chosen for study because they demonstrate the primary challenge inherent to dental imaging in general, namely the need to display clinically important features that are less prominent than the structures that surround them. The findings from this work are encouraging and support the ongoing study of *synthetic* dental radiography with sIOT, given the potential of this combination of software and hardware to offer a clinically viable and practical tool with many possible applications in the dental space.

Methods and materials

Preparing the specimens

The processing approaches reported in this work were developed using two datasets of images that had been collected previously of extracted and de-identified human tooth specimens following Institutional Review Board (IRB)-approval for their study. Detailed descriptions of the preparation of these two specimen groups have been published.[22,23] In brief, the specimens in one image set contained CAR present in posterior teeth.[22] Ground truth confirmation of the location and extent of these CAR lesions was obtained by visual inspection of the sectioned tooth after imaging. For imaging, the tooth of interest was mounted between two other extracted posterior teeth in a plastic block using modelling clay. This setup recreated interproximal spaces and approximated the attenuation of the surrounding tissues. The specimens in the second set of images contained artificially induced VRFs.[23] The VRFs were created using a steel wedge applied to decoronated premolars. The root canals were debrided, simulating an endodontic procedure, and some of the debrided canals were obturated with gutta-percha using a single cone technique, so as to avoid the chance that any dense obturation material would infiltrate the fracture. The individual specimens were stabilized using rubber cement, which also replicated the periodontal ligament space and were then mounted in plaster and crushed walnut shells to simulate alveolar bone and bone marrow spaces. When imaged, both specimen groups were positioned directly on the detector to reproduce the proximity achieved by an intraoral sensor location and then covered with 1 cm thick wax, simulating the soft tissues of the cheek.

Acquiring the images.

The images were acquired by three different dental imaging systems, including two commercially available

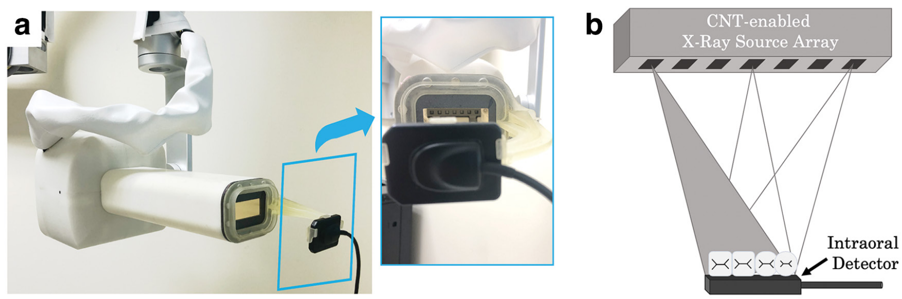

Figure 1 (A) The stationary intraoral tomosynthesis (sIOT) device has a similar appearance and operation to standard dental radiography equipment. However, the system geometry is quite different, as sIOT contains a stationary array of seven carbon nanotube (CNT)-enabled X-ray sources (expanded view). (B) A schematic representation of the sIOT geometry and operation. sIOT sequentially acquires the projection views, which are then processed for presentation as either a 3D stack of image slices, or in the case of this study, a set of synthetic 2D images.

systems and a prototype sIOT device. Standard digital imaging of the CAR specimens was accomplished using an Instrumentarium Focus Dental X-ray source combined with a Dentsply Sirona Schick 33 CMOS intraoral sensor, while VRF specimens were imaged by a Midmark Preva DC X-ray source utilizing a Carestream RVG 6100 CMOS intraoral sensor. The sIOT system (Surround Medical Systems, Morrisville, NC) contained a fixed array of seven CNT-enabled X-ray sources[12] and a CMOS intraoral sensor with a pixel size of 18.5 µm. The CNT-enabled sources are distributed over a 12° angle span (Figure 1).

As such, a single sIOT scan acquired with the X-ray tube positioned directly over the detector generated seven projection views that covered an angular range from −6° to +6°. Table 1 compares the operational parameters of these three systems.

Processing the images

The standard 2D images generated by the commercially available systems provided references against which the sIOT *synthetic* radiographs were compared. The sIOT *synthetic* radiographs are computer-generated 2D image displays of the processed 3D information collected by sIOT. As such, sIOT *synthetic* radiographs have the potential to combine the efficiency and familiarity of 2D imaging with the improved diagnostic accuracy of 3D imaging. Initial experience with sIOT image processing has demonstrated the value of displaying a set of *synthetic* images, each reflecting a different viewing angle, given the fact that a pathological site may be conspicuous at one angle but quite difficult to detect at another angle.[15] As such, the processing chains for sIOT generated a set of multi-view *synthetic* images. Currently, this set includes seven *synthetic* images, replicating the seven projection view angles collected at the time of the scan. As shown in Figure 2, two different image-processing chains were evaluated. Each processing chain was optimized to display a pathology with quite different image characteristics. Caries are typically diffuse image features and therefore do not require a very high resolution (high-frequency information) to visualize. Consequently, although the processing step of reconstruction inherently reduces high-frequency image information, carious lesions still tend to be displayed well in the reconstructed 3D image stack. Filtering was used to directly enhance these lesions prior to forward projection, which generates 2D images from the 3D image stack. However, fractures are high-frequency image features and therefore require a high resolution to visualize well. As such, high-frequency information from the projection images was used to generate the fracture-enhanced synthetic radiographs. Filtering was used to isolate potentially obscuring background features in the reconstructed 3D image stack, which were forward-projected and subtracted from the original projection images. In both cases, reconstruction was accomplished using a fan-volume adaptation of the simultaneous iterative reconstruction technique customized to the unique geometry of the sIOT device.[16]

Table 1 Operational source settings for imaging the caries adjacent to restorations (CAR) and vertical root fracture (VRF) specimens. The stationary intraoral tomosynthesis (sIOT) settings refer to each source in the distributed array

	CAR Imaging		***VRF Imaging***	
	Bitewing Radiography	sIOT	Periapical Radiography	sIOT
Tube Voltage (kV)	70	70	70	70
Tube Current (mA)	7	7	6	7
Exposure Time (ms)	80	100	160	50

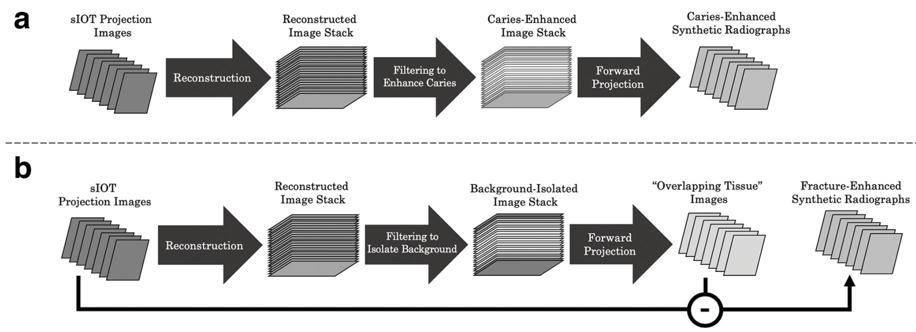

Figure 2 The image processing chains used to generate (A) caries-enhanced and (B) fracture-enhanced synthetic radiographs. Seven synthetic radiographs were generated for each stationary intraoral tomosynthesis (sIOT) scan, replicating the seven projection view angles collected at the time of the scan.

Results

Minimizing artefact
Tomosynthesis is by definition a limited sampling approach to 3D imaging. As a result, reconstruction of the 3D image space introduces artefact, especially in regions surrounding highly dense features. These shadowing and ringing artefacts related to restorations (Figure 3A) and obturation material (Figure 3C) can be quite prominent. Typically, the findings from a tomosynthesis scan are interpreted by scrolling through the image stack. However, interpreting these artifact-laden regions of the image stack can be difficult, since the artefact is not only distracting, but it can also hide pathology. Minimizing artefact in the images generated by an sIOT study was a primary motivation for the development of *synthetic* dental radiographs. Comparing the appearance of a reconstructed image slice to the appearance of a *synthetic* radiograph generated from the same reconstructed 3D stack (Figure 3B and D) demonstrates the effectiveness of the image processing chain to minimize dense-feature artefact in the *synthetic* images.

Seeing the interproximal space
Evaluating the contact area between adjacent teeth can be problematic, as tooth overlap and tissue superimposition is common in the standard 2D radiograph. By providing a set of multi-view *synthetic* images across an angle span of 12°, the sIOT system is more likely to provide a better view of the proximal tooth surfaces (Figure 4), decreasing the need for additional patient imaging.

Displaying CAR lesions
Figure 5 provides a representative example of a set of multi-view *synthetic* radiographs of a CAR lesion. As can be appreciated, these *synthetic* images are free of most artefact and have a similar general appearance to a standard radiograph, thereby improving the efficiency

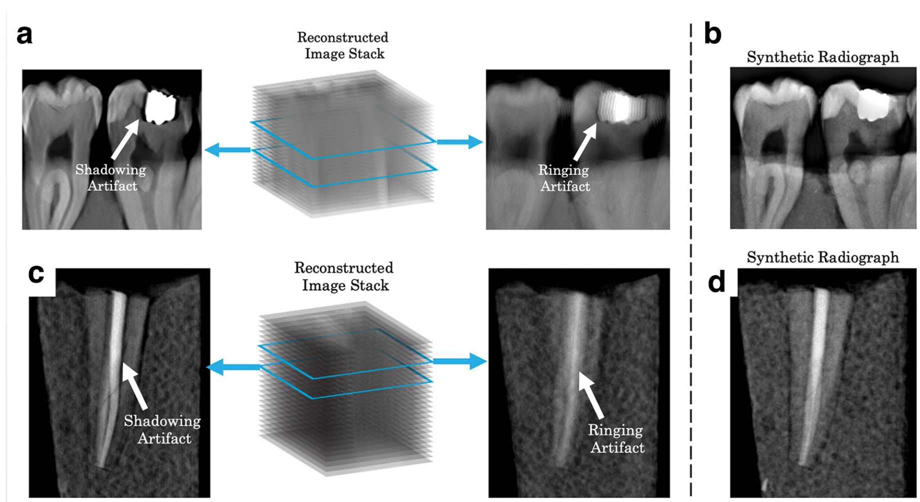

Figure 3 (A) Individual image slices from the reconstructed 3D stack generated by stationary intraoral tomosynthesis (sIOT) of a tooth containing a restoration. Note the shadowing and ringing artefact associated with the highly dense feature. (B) These artefacts are significantly reduced in the synthetic radiograph. Similarly, for an obturated tooth root, the shadowing and ringing artefacts resulting from the gutta-percha seen in the reconstructed image stack (C) are significantly reduced in the synthetic radiograph (D).

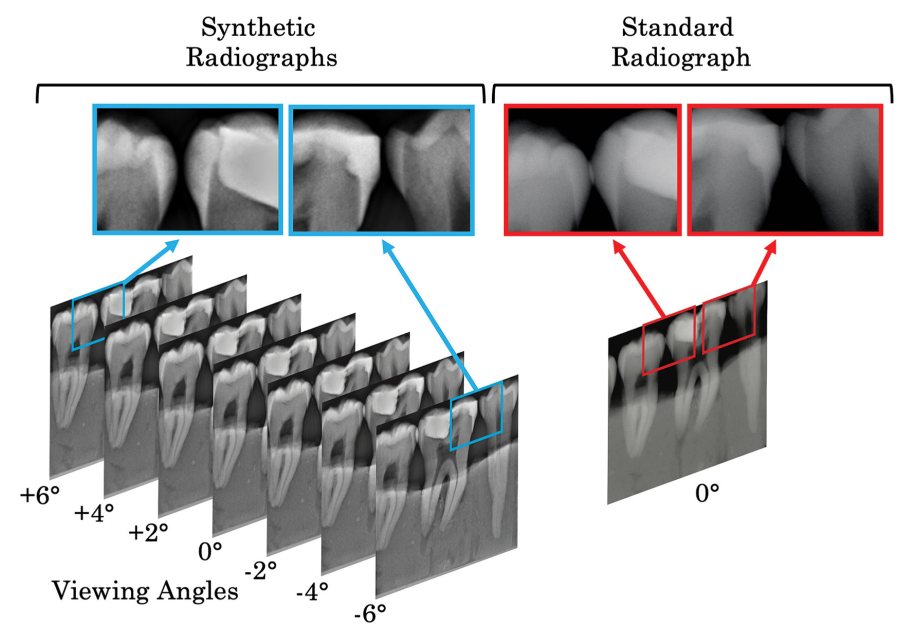

Figure 4 Synthetic radiographs compared to a standard radiograph of the same tooth specimens. The insets show the contact regions between teeth. Tooth overlap in the standard radiograph limits the visibility of the proximal tooth surfaces (red insets). However, the multiple views provided by the set of synthetic radiographs over the angle span of −6° to +6° can improve the chance of seeing the proximal surfaces well.

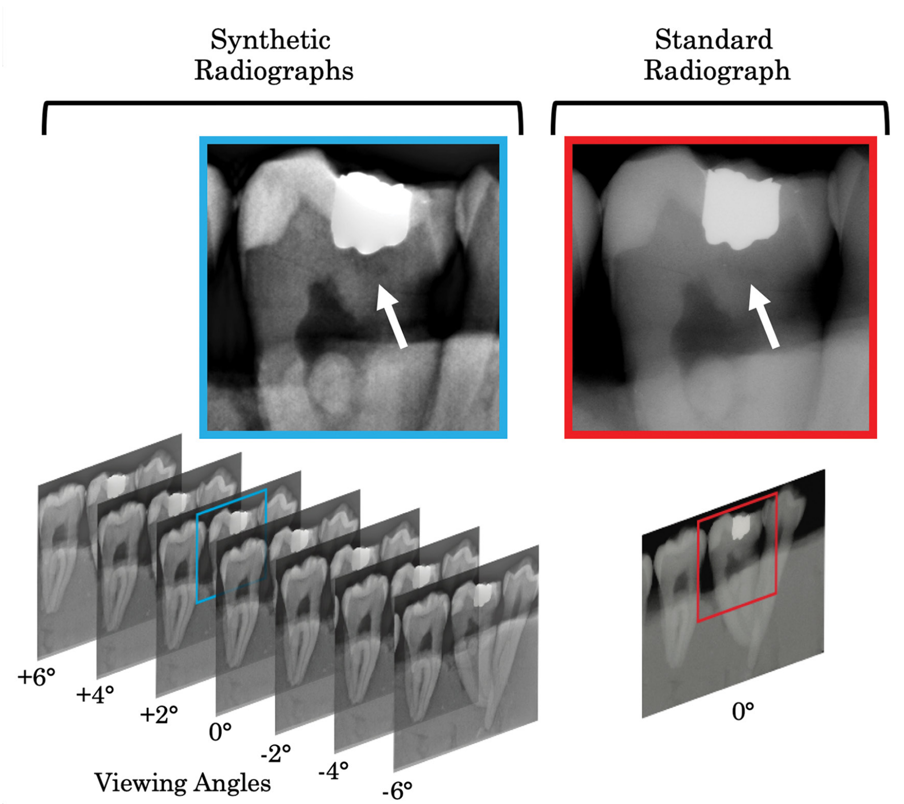

Figure 5 An example set of multi-view synthetic radiographs (left) generated by stationary intraoral tomosynthesis (sIOT) compared to a standard radiograph (right) of a tooth specimen with a carious lesion adjacent to a restoration (CAR). Note the improved conspicuity of the CAR lesion in the synthetic radiograph (blue inset) compared to the standard radiograph (red inset).

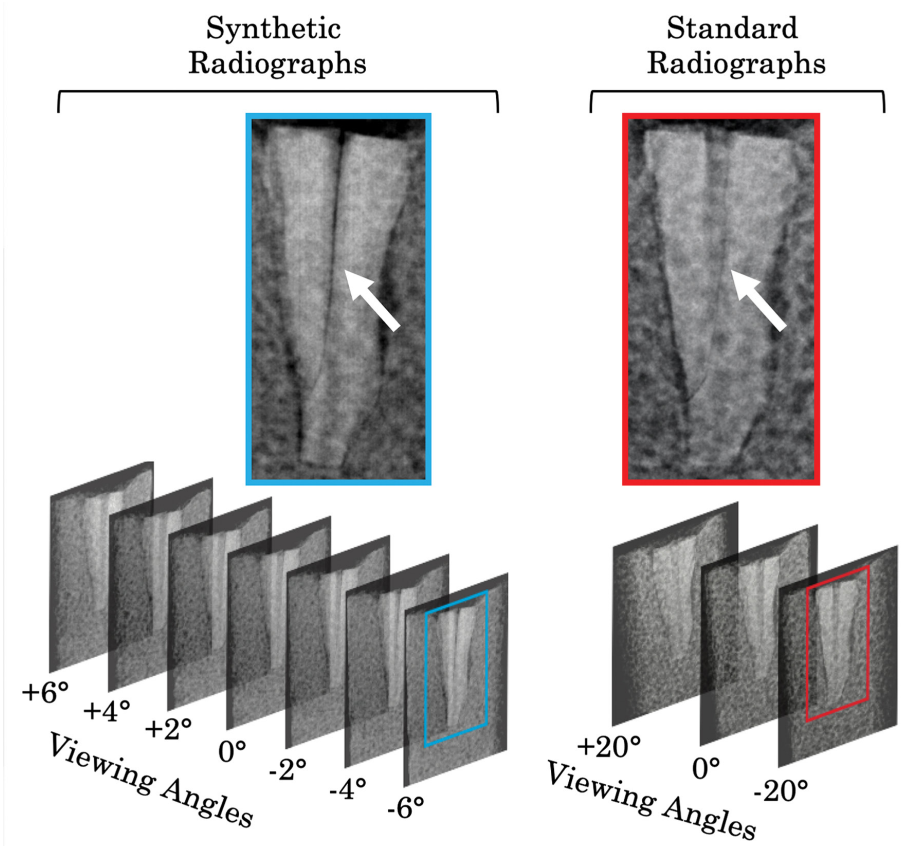

Figure 6 An example set of multi-view synthetic radiographs (left) generated by stationary intraoral tomosynthesis (sIOT) and three standard periapical radiographs (right) of a non-obturated tooth root specimen with a vertical root fracture (white arrows). The fracture was clearly displayed in the synthetic images generated from a single sIOT scan, particularly the −6° viewing angle (blue inset). For standard radiography, the X-ray source must be physically moved to acquire images from different angles. The fracture was best displayed in the standard radiograph acquired from a −20° viewing angle (red inset).

of their review. Additionally, by integrating the information in the 3D image stack into a single image, the *synthetic* image tends to display the carious lesion better than the standard radiograph.

Displaying VRFs

The set of multi-view *synthetic* radiographs of a non-obturated root specimen containing a VRF is shown in Figure 6. Demonstrating the value of a span of viewing perspectives, the VRF was best displayed in the *synthetic* radiograph representing a −6° viewing angle relative to the central projection. Similarly, identifying the fracture using standard radiography also required collecting oblique perspectives. As such, compared to the single sIOT scan, multiple standard radiographs were needed to ensure that the same information was available.

Discussion

A practical approach to 3D intraoral imaging would have many potential applications across all dental specialities. In addition to its potential for providing images with a higher diagnostic value than 2D radiography, it may be helpful during procedures. For example, clinicians could collect 3D information without having to move the patient to a separate room housing specialized imaging equipment, thereby allowing for the collection of 3D perioperative images in real time. sIOT is an experimental 3D imaging technology that holds promise. Its unique design includes an array of compact and rapidly responsive X-ray sources made possible by CNT technology.[12] As such, the overall size and operation of the device could be made to mimic standard dental radiography equipment. However, acceptance of this new technology also requires that the images generated by sIOT have a high clinical value while also presenting information in a familiar and efficient manner to dental practitioners. This work sought to improve both through the application of *synthetic* radiography. The *synthetic* radiograph represents a synthesis of the information from the original projection images and the many reconstructed slices of the 3D image stack. In recognition of the benefits of seeing pathology from different angles during dental imaging, the decision was made to display a set of multi-view *synthetic* radiographs. The perspectives represented in the multi-view set matched those collected at the time of the study.

For this study, CAR and VRF lesions were selected for study because they are challenging at multiple levels. First, both represent diagnostic scenarios in the clinic for which a 3D imaging tool would be beneficial. Additionally, both challenge tomosynthesis as an imaging modality, since they exemplify subtle pathologies adjacent to dense features. As a result, the processing chain producing the *synthetic* radiograph needed to improve the visibility of the pathological feature while also minimizing artefact. Finally, from an image processing standpoint, CAR and VRF lesions are features with very different image properties. CAR lesions are relatively diffuse features, while VRFs are thin and defined by sharp edges. As such, the development of image processing chains for both provided experience across a range of processing challenges.

This experience with *synthetic* radiography is limited, since it focused on qualitative assessments of extracted tooth models. However, the findings are encouraging, demonstrating the potential to improve the display of information generated by sIOT. As sIOT proceeds with clinical testing, the resulting library of clinical images will provide valuable data for the ongoing development of *synthetic* radiography. Based on this early experience, it is anticipated that novel image processing approaches will be needed as the unique technology of sIOT is applied to many challenging tasks presented by dental imaging.

Conclusion

Displaying the information collected by an sIOT study as a set of multi-view *synthetic* radiographs allows for the reduction of dense-feature artefact while preserving the appearance of pathological features that can be challenging to detect, including CAR and VRF. The addition of *synthetic* radiography to sIOT may offer a practical 3D intraoral imaging approach. This preliminary experience with extracted tooth models supports the ongoing study of this combination of software and hardware, which have many potential applications.

Acknowledgment

The authors would like to acknowledge support from the National Cancer Institute (1F30CA235892-01). Otto Zhou has equity ownership and serves on the board of directors of Xintek, Inc., to which the technologies used or evaluated in this project have been licensed. Jianping Lu has equity ownership in Xintek, Inc. Enrique Platin has a financial interest in Surround Medical Systems. Some of the authors are inventors of patents on the licensed stationary intraoral tomosynthesis technology used in this study. All of these relationships and activities are under management by institutional conflict of interest committees.

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