International Journal of Paediatric Dentistry 2006; **16:** 419–423 DOI: 10.1111/j.1365-263X.2006.00766.x

Dentinal carious lesion in three dimensions

F. S. L. WONG, N. S. WILLMOTT & G. R. DAVIS
Centre for Oral Growth and Development, Barts and The London, Queen Mary's School of Medicine and Dentistry, London, UK

Summary. *Aim.* The aim of this study was to show the morphology of the carious lesion in dentine in three dimensions (3D).
Design. A novel high-definition X-ray microtomography (XMT) scanner was used to scan 10 carious primary molars at a resolution of $15 \times 15 \times 15$ μm^3. A stack of ~640 XMT slices were recorded for each tooth. Using this data set and a volume rendering algorithm, each tooth was reconstructed in 3D. The VG Studio Max 1·0 visualization software package was used to make normal enamel and dentine transparent to show the carious lesions in 3D. A video film, comprised of the rendered images from 60 viewing angles rotating through 360°, was produced to show the carious lesion and its relation to the pulp in a three-dimensional perspective (http://www.smd.qmul.ac.uk/dental/oralgrowdev/biophysics/xmt/images/carious.mpg).
Results. These images showed that carious lesions in dentine were bowl-shaped. The pulp adjacent to the carious lesion was also observed to mimic the base of the bowl-shaped lesion.
Conclusions. It was concluded from the teeth studied that the shape at the base of the carious lesion in dentine is curved in 3D, rather than conical, as traditionally believed from two-dimensional image interpretation. Further 3D studies are needed to investigate whether the bowl-shaped carious lesions in dentine also apply to caries in other types of teeth.

Introduction

In terms of the histology of dentinal caries, conventional undergraduate teaching tends to refer to the papers by Levine [1] and Silverstone *et al*. [2], who concluded that the carious lesion in dentine has a characteristically conical shape, with the base at the enamel-dentine junction (EDJ) and the apex towards the pulp. However, clinical assessment of the shape of the carious lesion leads clinicians to teach students to use a round bur or a curved excavator to remove softened carious dentine [3], rather than a conical bur, which would more closely match the shape of the lesion reported from the histological studies. This disagreement may be caused by the disparity between the subjective impression of the clinician from clinical examination and extrapolation from two-dimensional (2D) histological sections to a three-dimensional (3D) shape [1,2]. Hence, the aim of the present study was to solve this conundrum by using a novel X-ray microtomography technique (XMT) to study the carious lesion in three dimensions.

Computed tomography (CT), invented by Hounsfield [4] in 1973, is a well-known medical technique for the examination of internal structures nondestructively. X-ray microtomography, developed originally by Elliott and Dover [5] in 1982, is a miniaturized version of CT that has a resolution of microns as opposed to millimetres. Since XMT produces a full 3D X-ray attenuation map of the scanned object, there is no compression of 3D information into two dimensions, i.e. the resultant image is a true representation with no superimposition, as in intraoral radiographs, for example. In addition, there is no physical sectioning using XMT, and thus, there is no loss of information between sections, as in the case of conventional microscopic techniques, such as optical microscopy and contact microradiography. Hence, by taking XMT slices of the whole object and stacking the slices, an accurate 3D map of the object can be produced.

Correspondence: F. S. L. Wong, Paediatric Dentistry, Centre for Oral Growth and Development, Barts and The London, Queen Mary's School of Medicine and Dentistry, Turner Street, London E1 2AD, UK. E-mail: f.s.l.wong@qmul.ac.uk

Materials and methods

In the present study, a high-definition XMT scanner [6] (Fig. 1), was used to scan 10 carious primary first molars. Visually, each tooth had an open carious lesion involving either the occlusal or the occlusal-approximal surfaces. The XMT system consisted of a microfocus X-ray source (X-Tek Ltd, Tring, UK), a kinematics stage, and an area charged couple device (CCD) camera with 1152×770 square detector elements. Earlier designs of XMT scanner using area detectors measured the same point in each projection with the same detector element. However, if the X-ray sensitivities of the individual detector elements are not uniform, this will result in ring artefacts in the reconstructed image. To overcome this problem, a novel time-delay integration CCD readout method is employed in this system to average out the characteristics of all the detector elements in each projection, thus eliminating these artefacts.

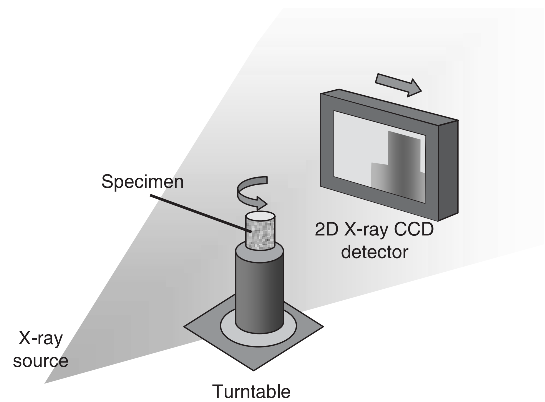

Fig. 1. Schematic diagram of the high-definition X-ray microtomography scanner.

Each tooth was mounted using epoxy resin on the cap of a specimen tube (Sterilin, Stafford, UK). The cap was attached to the centre of the kinematics stage (Fig. 2), and the specimen tube, with a piece of damp blotting paper to prevent desiccation, was screwed onto the cap to encase the specimen. Also mounted beside the tooth was a 2-mm-diameter, 99·99% pure aluminium wire (Alfa Aesar, Johnson Matthey, Materials Technology, London, UK). The whole assembly was then positioned inside the X-ray microtomography scanner and scanned. For each tooth, approximately 640 XMT slices were taken in the axial direction, taking approximately 24 h per scan.

After data collection, XMT images were reconstructed using a modified Feldkamp cone-beam algorithm with in-house software. The linear attenuation

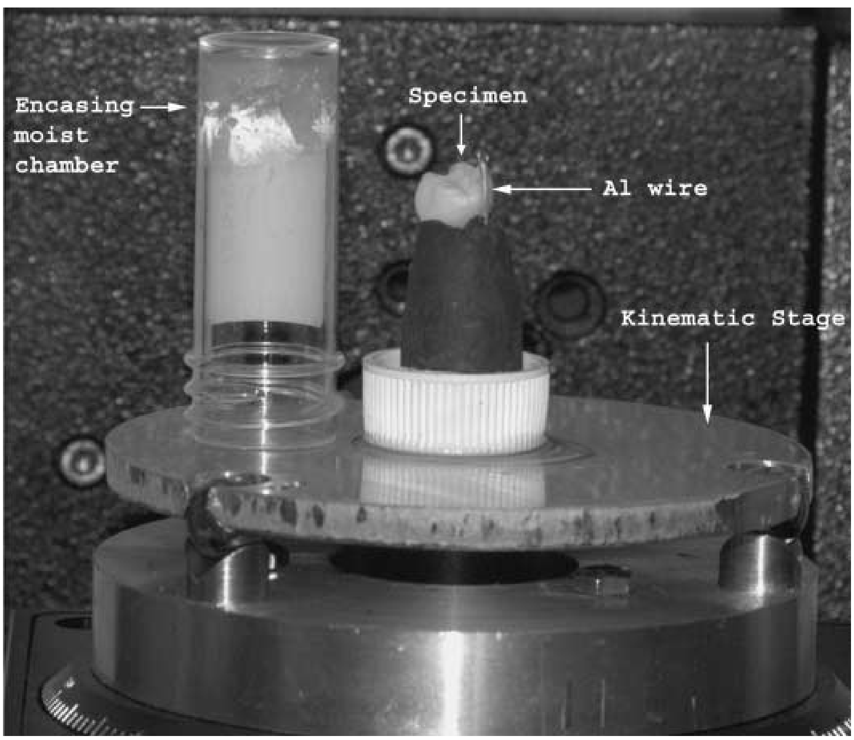

Fig. 2. Specimen on the kinematic stage of the X-ray microtomography scanner.

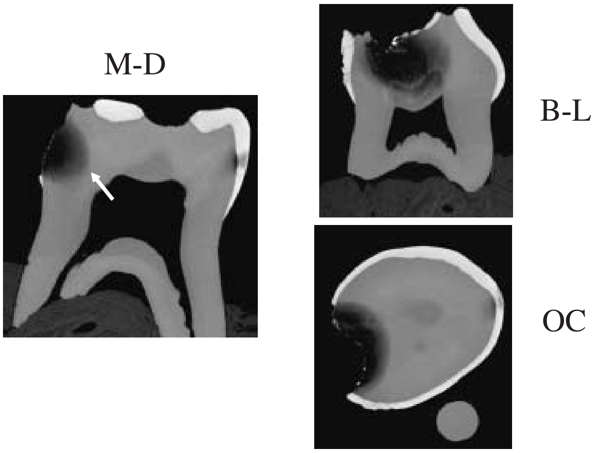

Fig. 3. X-ray microtomography slices viewed in three orthogonal planes: (M-D) mesial-distal; (B-L) buccal-lingual; and (OC) occlusal.

coefficients of the specimen were converted to 256 grey levels in the final output file. Visualization of the XMT slices and 3D rendering were carried out using VG Studio Max (Volume Graphics, Heidelberg, Germany) software package.

Results

The final XMT images were made up of voxels (volume elements) of $15 \times 15 \times 15$ μm^3. With the 3D data, virtual slices could be cut and visualized in any plane. Three typical slices in the mesio-distal (M-D), bucco-lingual (B-L), and occlusal (OC) planes through the carious lesion of one primary molar are shown in Fig. 3. The shape of the dentinal carious lesion, as observed in all the planes, had a wide base at the EDJ with a rounded base towards the pulp. In the M-D plane, the base was more pointed (arrowed in Fig. 3) than that seen in the other two planes, and therefore, the lesion could arguably be described as having a quasi-triangular shape. These features were also observed in the other teeth which were scanned.

In order to render the image in three dimensions, the boundary between sound and carious dentine needed to be defined. Unfortunately, no value of mineral concentration for this boundary could be found in the literature. In a more detailed analysis of the same data set in the present study, Willmott [7], using the mineral concentration distribution curves of a block of sound dentine, estimated the mineral concentration of sound dentine to be more than 1·2 g cm^{-3}. Using this value as the boundary for carious dentine, the teeth were rendered three dimensionally to show the shape of the dentinal caries. The rendered images for two of the 10 teeth are shown in Fig. 4. The enamel and dentine were rendered semi-transparent to show the carious lesion and the pulp. These images show that the carious lesions are bowl-shaped, with their round bases towards the pulps. They also show that the shape of

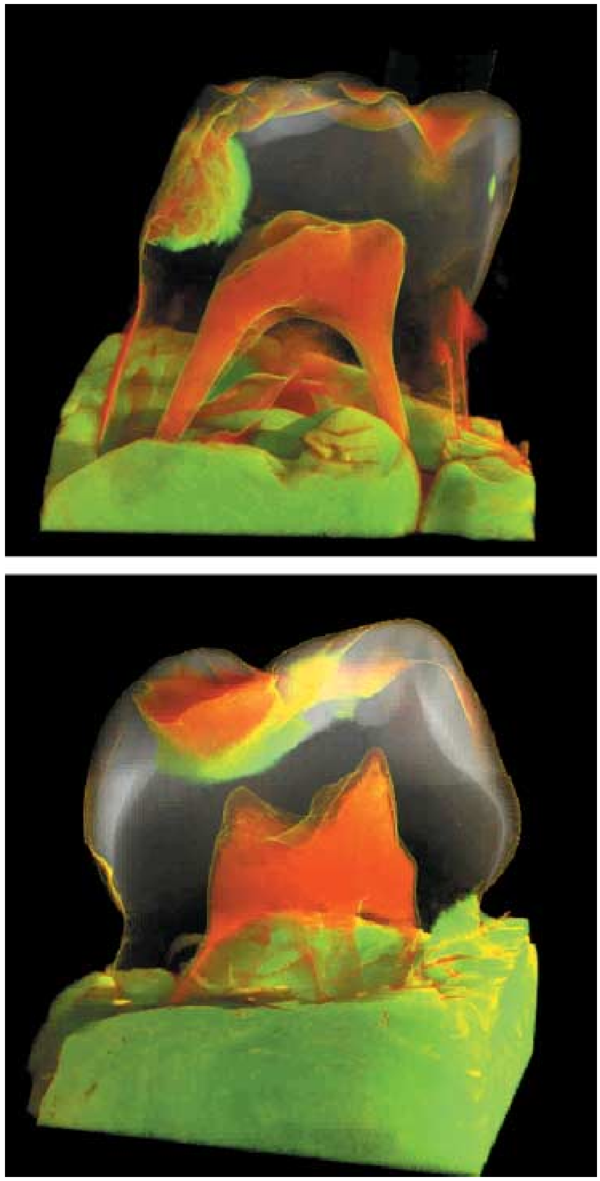

Fig. 4. Three-dimensional reconstruction of carious lesions in two primary first molars. The enamel and dentine were made semi-transparent. The carious lesion was characteristically bowl-shaped with matching pulpal recession adjacent to its base.

the adjacent pulp mimics the shape at the base of the carious lesion. In printed format, it is difficult to show images in a 3D perspective. Figure 4 shows the 3D image from only one viewing angle. With the XMT data, views can be generated from an infinite number of angles. A video film, capturing 600 views, was generated to show the rendered images rotating through 360°. This gives us a better understanding of the relationship between the carious lesion and the pulp in three dimensions. This video can be found at: http://www.smd.qmul.ac.uk/dental/oralgrowdev/biophysics/xmt/images/carious.mpg

Discussion

Silverstone *et al*. stated that 'it is useful to have a mental image of the characteristic morphology of dentine lesions during the preparation of a cavity for restoration' [2]. However, there are very few references in the literature describing the morphology of the dentinal carious lesion. From the images obtained by microradiography [1] and polarizing light microscopy [2], dentinal carious lesions were described as characteristically conical. This conclusion was deduced from the quasi-triangular shape of the lesion observed from the 2D sections of the teeth. In this study, a XMT slice in a particular orientation (M-D in Fig. 3) could be thought to have a similar triangular shape to that from the earlier studies. However, when the lesion was rendered in three dimensions, the morphology of the lesion was undoubtedly bowl-shaped (Fig. 4). Hence, the triangular shapes observed in 2D sections are likely to be produced by the direction of the sectioning plane.

The volume images in Fig. 4 and the video show that the roof of the pulp matches the shape of the dentine lesion, indicating that the pulp generally responds to the carious stimuli by laying down reactionary dentine in three dimensions. From this observation, if a clinician uses a round bur or a curved excavator to remove carious dentine, the prepared cavity will conform to the outline of the natural carious lesion and the shape of the pulp.

In this study, $1{\cdot}2\ \mathrm{g\ cm^{-3}}$ was used as the mineral concentration to delineate the boundary between sound and carious dentine. The authors could not find any studies which reported the range of mineral concentration in carious dentine. This figure was used based on a detailed analysis of the mineral concentration of carious and sound dentine by Willmott [7]. It was found that the mineral concentration gradient in sound dentine was much lower than that seen at the carious lesion boundary. Thus, it has little effect on the observed morphology of the lesion. If a lower level of mineral concentration was used, only the lesion depth would be reduced; the shape would remain unaffected.

This study shows that it could be erroneous to deduce 3D shape from 2D data. X-ray microtomography has the distinct advantage over conventional microscopic techniques of being a 3D technique. Although XMT cannot be used *in vivo* because of its high radiation dosage and length of scan time, it provides a novel way to study dental caries with a view to translating the finding to clinical application. Further 3D studies are needed to investigate whether the bowl-shaped carious lesions in dentine also apply to other types of teeth.

What this paper adds

- The authors describe a novel X-ray microtomography method to study carious lesions in three dimensions (3D).
- In all of the first primary molars included in the study, the base of carious lesion was seen to be curved, not conical, in 3D.
- The results illustrate that the lesion effectively mimics the shape of the pulp in these teeth.

Why this paper is important to paediatric dentists

- The results of this study suggest that curved instruments may well be the most appropriate for caries removal.

Acknowledgements

The authors would like to thank Professor J. C. Elliott for his guidance on the development of the XMT scanner and Mr S. Figaro for his technical support. The development of this novel XMT scanner is supported by EPSRC grant GR/R28911/01.

References

1 Levine RS. The microradiographic features of dentine caries. Observations on 200 lesions. *British Dental Journal* 1974; **137**: 301–306.
2 Silverstone LM, Johnson NW, Hardie JM, Williams RAD. *Dental Caries: Aetiology, Pathology and Prevention*. London and Basingstoke: The MacMillan Press Ltd, 1981.
3 Kidd EAM, Smith BGN, Watson TF. *Pickard's Manual of Operative Dentistry*. Oxford: Oxford University Press, 2003.

4 Hounsfield GN. Computerized transverse axial scanning (tomography). 1. Description of system. *British Journal of Radiology* 1973; **46**: 1016–1022.
5 Elliott JC, Dover SD. X-ray microtomography. *Journal of Microscopy* 1982; **126**: 211–213.
6 Davis GR, Elliott JC. X-ray microtomography scanner using time-delay integration for elimination of ring artefacts in the reconstructed image. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1997; **394**: 157–162.
7 Willmott NS. *X-ray microtomographic study of dentinal caries, and its removal, in deciduous teeth*. Master of Clinical Dentistry Dissertation. London: Barts and The London, Queen Mary, University of London, 2003.