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Behaviour of primary incisor caries: a micromechanical study

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Summary. *Objectives*. To date, there has been no attempt to assess the mechanical properties of the entirety of a smooth-surface carious lesion in primary teeth, despite the fact that these lesions are not only common, but clinically challenging. Therefore, the aim of this study was to describe the hardness and modulus of elasticity across smooth surface lesions of primary incisors.

Study design. An *in vitro* study of the micromechanical properties of primary incisors.

Materials and methods. Carious primary incisor teeth were set in resin, sectioned and polished. A series of indentations using the ultra-micro-indentation system were conducted in fully hydrated carious and sound dentine from the minimally affected pulpal region towards the tooth surface. A single set of indentations were duplicated for sound dentine.

Results. Although the mechanical properties of the carious dentine varied between the test teeth, the median hardness of the surface, middle and inner (pulpal) region of the carious dentine was 0·01, 0·10 and 0·28 GPa, respectively. The modulus of elasticity of the surface, middle and inner (pulpal) carious dentine was 0·12, 2·16 and 5·98 GPa, respectively. The mechanical properties of the sound dentine varied less, and were consistent between the pulpal and surface regions. Examination of the individual series of indentations indicated that, although the majority of the test teeth showed a decrease in the mechanical properties from the 'unaffected dentine' to the surface of the lesion, in the last 300–500 μm, both the hardness and modulus of elasticity showed a dramatic increase.

Conclusions. This study has confirmed that the carious process has a deleterious effect on the mechanical properties of dentine in primary incisors. This, in turn, increases the likelihood of restorative failure. However, the slight increase in mechanical properties seen at the surface of the carious lesion suggests an increase in mineral content.

Introduction

Despite the fact that it is largely preventable, dental caries remains one of the most common chronic diseases of childhood [1]. Whilst over half the paediatric population are caries-free in many developed countries, certain groups of children do experience disproportionate amounts of caries, much of which remains untreated [2]. In these high-risk young children, the carious process often involves the enamel and dentine of the smooth (labial and palatal) surfaces of the primary incisors. Traditional approaches to the management of these carious primary incisors involves either their extraction or the removal of the carious tissue followed by placement of an adhesive resin or glass ionomer cement restoration [3]. The latter approach can be clinically challenging and prone to failure not least because of the limited cooperation associated with some young children [4–6]. As a result, residual caries often remains in these teeth with or without the placement of temporary restorations.

Historically, management of dental caries in general has involved the mechanical removal of the infected, degraded tooth tissue and its replacement by an inert restorative material. The amount of dentine removed prior to the placement of the restorative material is essentially determined by clinical assessment of the hardness (and colour) of the remaining tissue. Such an approach is highly subjective with the amount of dentine removed varying

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significantly between clinicians [7]. The more tissue removed, the weaker the residual tooth structure, making restorative failure more likely. This is a particular problem in the case of primary incisors, which are relatively small with a limited surface area for restorative bonding even in the healthy state.

Contemporary understanding of the carious disease process is that of a chronic, initially reversible infectious disease in which bacterial acids demineralize the hard tooth tissues by causing a loss of ions such as calcium and phosphate, followed, eventually, by degradation of the organic protein substructures. This concept implies that caries is a dynamic process of demineralization and that the dental tissues have the potential to remineralize. Clinical studies support this hypothesis. Irrespective of how little tissue is removed, sealing carious dentine from the oral cavity results in an increase in clinically assessed hardness and radiographic lack of lesion progression, which have been interpreted as evidence of remineralization of dentine [8,9]. Other methods of assessing the processes within carious dentine have included monitoring the microbial load [10–12], the colour [13] and the wetness [14] of residual dentine. Assessment of colour and wetness are essentially subjective, whilst monitoring microbial loads requires the removal of dentine, which results in a change in the environment that is difficult to quantify. There is currently relatively little quantitative information regarding the remineralization processes which occur within dentine, which, in comparison with enamel, is a very complex structure.

The hardness of a tissue may be defined as its ability to resist permanent indentation [15], and the modulus of elasticity (stiffness) is the ratio of stress to corresponding strain below the proportional limit. The modulus of elasticity provides an indication of the amount of deformation that may occur in a tissue when a load is applied [16]. Measuring hardness has been shown to be a reasonable method of examining the mineral content of calcified tissue, including teeth [17–19]. Much of this work has concentrated on permanent teeth [20–23] with a few studies on primary molars [24,25]. Using an ultra-micro-indentation system (UMIS), decreases in the hardness and modulus of elasticity of dentine from carious primary molars have been shown to be directly related to the mineral content (measured using scanning electron microscopy backscattered electron microscopy) [19].

To date, there has been no attempt to assess the mechanical properties of the entire smooth-surface carious lesion in primary incisors, despite the fact that these lesions are not only common but clinically challenging. The aim of this study was to describe the mechanical properties across carious dentinal lesions in primary incisors with the intention being to increase understanding of the demineralization processes which occur.

Materials and methods

Eight primary central incisors which had been extracted because of caries were collected for this study. The inclusion criteria were: (1) teeth were removed from children less than 4·5 years old; (2) there should be no dental abscess associated with any of the teeth; and (3) there must be at least one clinically apparent carious lesion on the labial surface of each tooth.

At time of extraction, all the teeth were immediately placed into deionized water with a small number of thymol crystals to inhibit bacterial growth. Each tooth was encased in cold-cured epoxy resin and sectioned through the centre of the lesion (which coincided in all teeth with the centre of each tooth) in the labial–palatal longitudinal plane using a water-cooled, diamond-impregnated circular saw rotating at 150 r.p.m. (Labcut 1010, Agar Scientific Ltd, Standsted, UK). The cut surface was then polished with successively finer grades of sandpaper and finally with 6 μm polycrystalline diamond suspension. A grid reference was scored on the polished surface with a scalpel blade to allow orientation of the specimen for the experiments. Once prepared and while waiting testing, the samples were kept fully hydrated in deionized water with a small number of thymol crystals. The effect of storage of carious dentine in deionized water is unknown, although it has been shown to affect enamel and dentine of sound teeth [26].

The use of the UMIS to evaluate the hardness and modulus of elasticity of small specimens of enamel and dentine has been reported previously [24,25]. When each specimen was ready for testing, it was placed on the work table of the UMIS with the polished surface upwards. The area to be tested was then determined with the aid of the microscope associated with the UMIS. Depending on the size of the carious lesion, between four and six lines of indents were made in each (Fig. 1), with the first series starting

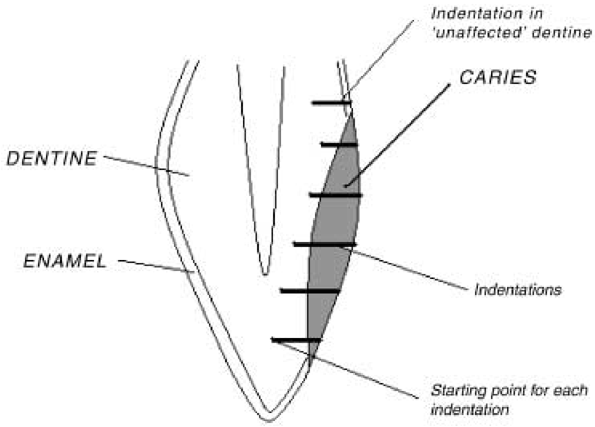

Fig. 1. Diagrammatic representation of the layout of the indentations.

at the incisal region of the tooth and subsequent arrays approximately 500 µm apically. The first indentation in an array began in sound or minimally affected dentine, 200 µm from the most pulpal edge of the discoloration front, with each subsequent indentation in each series 100 µm labially to first indent. The last indent was within 100 µm of the tooth surface. Attempts were made to follow the path of the dentinal tubules. The number of indents per series depended on the depth of the carious lesion, but varied between 10 and 25 indentations per line. For all teeth, a single series of indentations was also carried out in unaffected dentine apical to the lesion by way of a control. These control indentations were conducted under sound enamel, with the last impressions placed within 100 µm of the enamel dentine junction. Each indentation was carried out in 25 increments to a maximum force of 5 mN with a Berkovich indenter. The dentine was kept 100% hydrated at all times by the placement of droplets of distilled water over the entire carious lesion.

The software associated with the UMIS calculates the hardness as a function of the depth of penetration of each indentation. The UMIS calculates the hardness at each of 25 increments to a maximum force of 5 mN, and the mean hardness is calculated from this to give the overall hardness for each indentation. The modulus of elasticity for each indentation is calculated as a function of the unloading curve at the maximum depth of penetration [25].

The hardness and modulus of elasticity for the outer, middle and inner thirds of the carious lesion of each tooth were determined by combining and averaging the values obtained for the four to six arrays conducted for each tooth. The inner and outer dentine regions combined all indentations within 500 µm of the pulp and within 500 µm of the carious lesion surface, respectively. The middle region was all indentations between these two regions. Additionally, changes in the mechanical properties (hardness and modulus of elasticity) were graphed for each tooth, from which general trends across the carious lesion could be determined. These results were compared with the series of indents carried out in the unaffected dentine of each tooth.

Results

A single value for the hardness and elastic modulus of carious dentine in each tooth could not be determined since these properties varied significantly across each lesion. Therefore, the mechanical properties of the inner, middle and surface thirds of all test teeth were combined, and an average, median and range for each third were calculated (see Table 1). Table 1 shows that the mechanical properties of carious lesions in the primary dentition decreased from the inner portion to the surface (as shown by the median and average values for each region), although the actual values vary significantly between each specimen (as shown by the wide range of values). Table 2 shows the mechanical properties of the three regions for the control, i.e. sound, dentine. The average percentage reductions in hardness and modulus of elasticity of the eight test teeth at the surface, middle and inner third of the carious lesions were compared to those of the unaffected dentine in

Table 1. Mean ± SD, median and range for the hardness and modulus of elasticity of carious primary dentine in three specified regions of primary carious dentine.

Dentine region	Hardness (GPa)			Modulus of elasticity (GPa)			Number of indentations (measurements)
	Mean ± SD	Range	Median	Mean ± SD	Range	Median	
Surface of carious lesion	0·07 ± 0·1	0·0007–0·30	0·01	0·99 ± 1·45	0·01–4·88	0·12	379
Middle of carious lesion	0·15 ± 0·14	0·01–0·47	0·10	3·50 ± 3·67	0·07–15·3	2·16	385
Inner portion of carious lesion	0·29 ± 0·16	0·05–0·72	0·28	7·77 ± 5·05	2·07–28·33	5·98	390

Table 2. The mean values ± standard deviation, median and the range for the hardness and modulus of elasticity of sound primary dentine in three specified regions of primary sound dentine.

Sound dentine	Hardness (GPa) mean ± SD	Hardness range (GPa)	Median (GPa)	Modulus of elasticity (GPa) mean ± SD	Modulus of elasticity range (GPa)	Median (GPa)	Number of indentations (measurements)
Surface	0·40 ± 0·18	0·22–0·65	0·32	8·96 ± 3·14	5·6–13·2	8·10	60
Middle	0·45 ± 0·18	0·39–0·73	0·39	10·98 ± 2·53	6·45–13·50	11·39	64
Inner	0·39 ± 0·16	0·16–0·62	0·37	11·14 ± 4·35	6·95–12·82	9·53	57

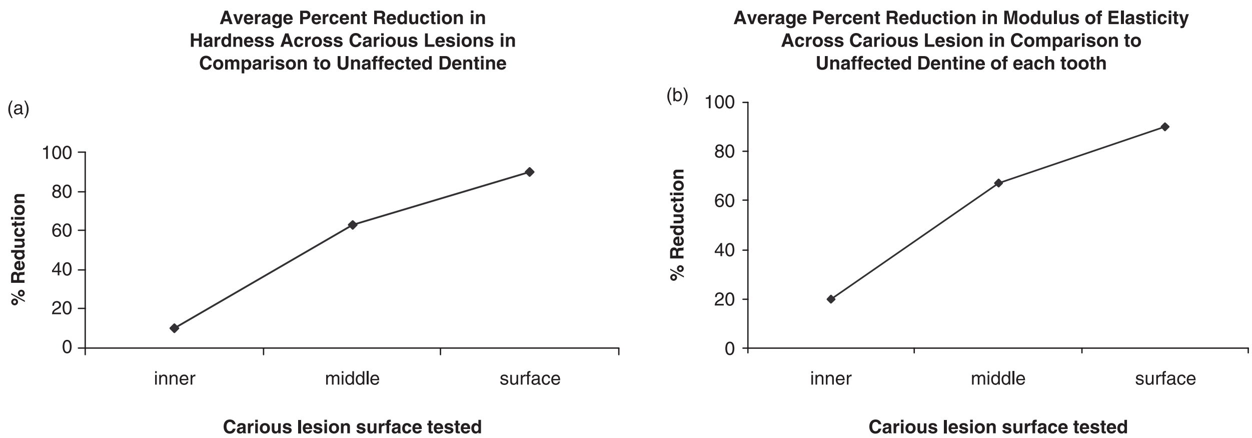

Fig. 2. Percentage reduction in (a) hardness across carious lesions and (b) modulus of elasticity across carious lesions compared with unaffected dentine.

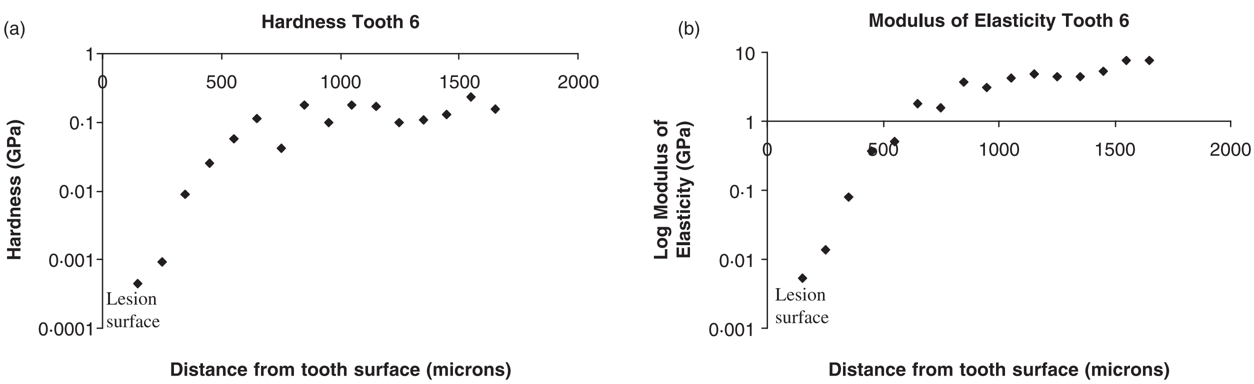

Fig. 3. (a) Hardness of a single array in tooth 6 showing a marked increase in hardness from the surface of the lesion pulpally and (b) modulus of elasticity of a single array in tooth 6 showing a marked increase in modulus from the surface of the lesion pulpally. Note the log scale.

the same regions (Fig. 2). These graphs demonstrate the significant reduction in the hardness of carious dentine from the inner aspect through to the surface of the lesion. The outer third of the carious lesions had, on average, only 10% of the mechanical properties of sound dentine. From these graphs, it is also obvious that, although the indentations began 200 μm pulpal to the discoloration front (i.e. to the apparent front of the carious lesion), there was already a reduction in both the hardness and modulus of elasticity of 10% and 20%, respectively, in this region.

Closer examination of the trends in mechanical properties across individual arrays reveals two distinct patterns. Two of the teeth (teeth 1 and 6) showed a continuous reduction in hardness and modulus of elasticity from the more pulpal ‘unaffected dentine’ towards the outer surface of the lesion (Fig. 3). The

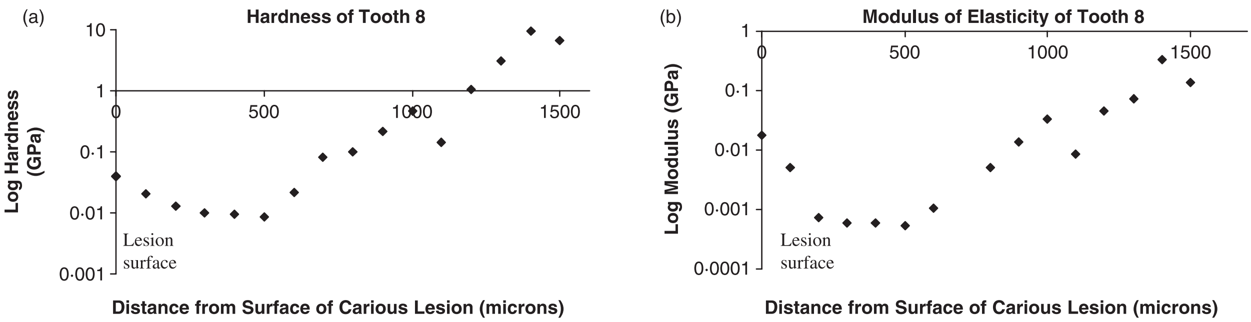

Fig. 4. (a) Hardness of a single array of tooth 8 showing an increase in mechanical properties 500 μm from the surface and (b) modulus of elasticity of a single array of tooth 8 showing an increase in mechanical properties 500 μm from the surface.

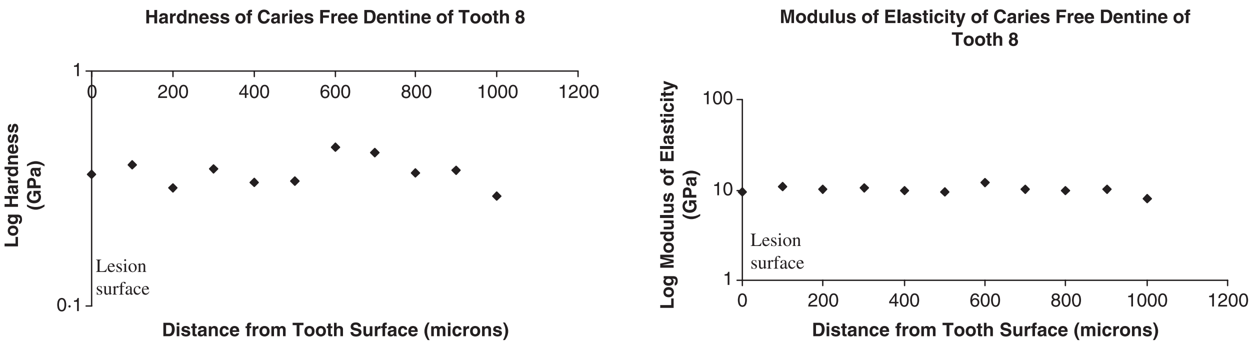

Fig. 5. (a) Hardness of a caries-free region of tooth 8 showing no change in mechanical properties from the surface of lesion pulpally and (b) modulus of elasticity of a caries-free region of tooth 8 showing no change in mechanical properties from the surface of lesion pulpally.

remaining teeth showed a decrease in the mechanical properties from the 'unaffected dentine' to the surface of the lesion until the last 300–500 μm, where both the hardness and modulus of elasticity increased (Fig. 4). This second pattern was seen consistently across all the arrays in teeth 2–5, 7 and 8.

In the caries-free controls, there was no change in mechanical properties across the width of the dentine (Fig. 5).

Discussion

At present there is limited information in the literature on the mechanical properties of carious lesions, particularly those in the primary dentition. Hosoya and colleagues [27] investigated the mechanical properties of carious dentine on deciduous anterior teeth. In their study, seven teeth (four primary canines and three primary anterior incisors) were dehydrated and tested with a conventional microhardness tester at a 15-g load. However, the very soft nature of the 'infected zone' of the carious lesion meant that accurate residual impression measurements in this zone were impossible, so the discussion was limited to hardness values of dentine under and surrounding the carious lesion [27]. The UMIS used in the current study allows for conditions of constant hydration which more closely reflect the *in vivo* environment [28]. The effect of hydration on the mechanical properties of primary tooth dentine is significant with a 10-fold increase in both hardness and elastic modulus being recorded when specimens were dehydrated [28].

The inner third of the carious dentine lesion (nearest its advancing front) had an average hardness and modulus of elasticity of 0·29 ± 0·16 and 7·77 ± 5·05 GPa, respectively. The teeth chosen in this study had severe caries which had caused demineralization of the inner dentine. Therefore, it is not surprising that the mechanical properties were significantly worse than would be expected in sound teeth. From the inner region, the mechanical properties deteriorated progressively towards the surface of lesion at the cavity floor where the lowest values for hardness and modulus of elasticity were found ($0{\cdot}07 \pm 0{\cdot}1$ and $0{\cdot}99 \pm 1{\cdot}45$ GPa, respectively). Conversely, the mechanical properties of sound dentine from the pulpal (inner) to surface of the dentine (near the amelo-dentinal junction) did not show the same deterioration, with relatively constant hardness and modulus of elasticity values recorded across the width of the dentine.

Marshall and colleagues investigated the mechanical properties of carious lesions in permanent teeth (type not specified) [21]. They used an atomic force microscopy indentation instrument to determine the hardness and modulus of elasticity of fully hydrated carious peritubular and intertubular dentine. These authors showed graphically (but not quantitatively) that the mechanical properties (hardness and modulus of elasticity) of carious lesions decreased significantly from the apparently normal dentine into the discoloured regions, consistent with the present study. However, they did not report any increase in properties at the surface of the lesions in their teeth.

The actual values for the mechanical properties of sound dentine reported in the present study are low in comparison to previous studies on both primary or permanent teeth [24,25,29–32]. It is often difficult to compare results from other studies because of differences in test protocol (e.g. indentor shape); however, apart from the fact that incisors rather than molars were tested, the methods used by Angker and colleagues [24] were very similar to the present study. Therefore, the difference in mean values for sound dentine between these two studies is a little surprising. It is possible that the orientation of indentation arrays between the molar studies (mesial–distal) compared with the present incisor (lingual–labial) may have influenced these results. Alternatively, the incisors used in the present study were very carious whereas, although not reported by the authors, the level of decay may have been lower in the study by Angker and colleagues [24].

The results of the present study show that the mechanical properties of dentine change dramatically throughout the carious lesion, which suggests that the mineral content is also affected. This will have implications on the quality or dependability of any adhesive bond that may be formed between tooth substrate and restorative material. Yoshiyama [33] suggested that the lower tensile strength of caries-infected dentine itself will affect the bond strength for resin materials. Furthermore, the dramatic reduction in modulus of elasticity seen in this carious dentine may mean that it will flex more than any restorative material placed upon it when loaded under occlusal function. These differential flexural properties would cause further deterioration in the integrity of the bond and may explain the failure of some restorations when placed on carious primary incisors.

Whilst there was a general deterioration in the mechanical properties of carious dentine across the smooth surface lesions from the inner to the outer third, two distinct trends were noted. Two teeth showed a continuous reduction in hardness and modulus of elasticity from the inner dentine right through to the surface of the lesion. This is consistent with the view that the dentine at the surface of a carious lesion will be highly infected and completely demineralized, with most of the remaining collagen severely denatured. This region is considered to be ‘infected dentine’ and unable to be remineralized [34]. Conversely, six of the teeth showed a similar deterioration in the mechanical properties from the inner dentine outwards until the final 300–500 μm beneath the surface, where the mechanical properties increased. It is possible that this is evidence of natural remineralization processes taking place in the oral cavity, resulting from the capacity of saliva to promote mineral deposition in open lesions [35]. It is likely that the capacity for remineralization is greater in smooth-surface lesions compared with occlusal lesions because of the relative ease of exposure to saliva and other factors such as fluoride. In this study, there is no information on the life history of the teeth nor of the environment of the oral cavity from which they were removed. However, partial remineralization appears to have occurred in carious primary incisor teeth which were probably removed from a child with extensive caries and whose oral cavity was essentially a hostile environment. Future management strategies may focus on optimizing and enhancing this remineralization process by promoting a favourable oral environment.

Contemporary understanding of the processes involved in the de- and remineralization of dentine remains limited. This study has confirmed that the carious process has a deleterious effect on the mechanical properties of dentine in primary incisors. This, in turn, increases the likelihood of restorative failure. However, the increase in mechanical properties seen at the surface of the carious lesion suggests an increase in mineral content. This may reflect a process of remineralization resulting from exposure to the oral environment. Further *in vivo* studies are required to evaluate the effect on carious dentine of exposure to various fluoride formulations and to casein phosphopeptide amorphous calcium phosphate [found in Recaldent™ (Cadbury Schweppes Pty Ltd, City, Melbourne, Victoria, Australia) and GC Tooth Mousse (GC Corporation, Itabashi-ku, Tokyo, Japan)]. Increased understanding of what promotes and what inhibits the mineralization of carious dentine is still required. The opportunity to promote the remineralization of primary incisor caries offers a more conservative management strategy that would be most attractive to clinicians and their young patients.

What this paper adds
- This study increases the understanding of the effect of the carious process on the properties of dentine in primary incisor teeth.
- This study highlights the catastrophic reduction in the hardness of carious dentine caused by the demineralization process.

Why this paper is important to paediatric dentists
- In order to successfully restore a tooth it is necessary to re-establish the mechanical properties of the residual tooth structure to those of unaffected tissue.
- Understanding that carious process causes significant softening of dentine through mineral loss is important if strategies to maintain these teeth based upon remineralisation rather than traditional surgical restoration are to be successful.

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