Key Words
Caries diagnosis
Electrical conductance
Enamel

Abstract
Electrical conductance measurements are being used experimentally to diagnose caries. Current equipment, e.g. the electronic caries monitor (ECM), uses a probe to scan occlusal fissures. For full-mouth examination this method is rather time-consuming. A method with which only one measurement is needed for an entire (occlusal) surface would be preferable. However, the enlargement of the area being measured will influence the conductance. It was the purpose of this study to investigate the relationship between the electrical conductance of human teeth and the enamel electrode area, and to compare the range of results of surface measurements with those of the scanning method. Twenty-five sound extracted teeth were selected for the study. The reference electrode of the ECM was connected to the roots. The buccal surface was blotted dry, and a coloured dentifrice was syringed in increments onto the surface. After each increment the surface was photographed together with a metric reference, a conductance measurement was performed by holding the ECM probe tip in the dentifrice, and the ECM reading was recorded. For each tooth between 5 and 10 increments were applied and measured. The photographs were digitised and the electrode areas were calculated. A least squares curve fitting procedure yielded a linear relationship between conductance and electrode area (0.88 ≤ R² ≤ 1.0, mean R² = 0.97). For most teeth the threshold for dentinal caries as used for scanning ECM measurements (ECM reading = 6.00) was reached only when the electrode area exceeded 12 mm². For 6 teeth this conductance was already reached between 5 and 12 mm². Electrical conductance measurements of the occlusal surfaces of 18 teeth, with electrode areas as projected two-dimensionally of between 5 and 10 mm², showed only 3 measurements above the threshold. None of those 3 came from the group of 6 teeth mentioned before. It was concluded that the relationship between electrical conductance of teeth and electrode area is linear. It was also concluded that when electrical conductance measurements of occlusal surfaces are to be made, the threshold for dentinal caries will probably have to be shifted to a higher conductance level to limit false-positive results.
Recently some alternative methods for diagnosing carious lesions have been developed, that may become important adjuncts to or replacements of the traditional methods, [Pitts, 1991]. One of the most promising new methods is electrical caries measurement.

It has been demonstrated that the low electrical conductance of a tooth is primarily caused by the enamel. At locations where the enamel has a larger pore volume (due to hypo- and/or demineralisation), electrical conductance increases considerably. It has proved to be possible to use this characteristic behaviour in the early detection of carious lesions [Pincus, 1951]. The currently available instruments use a small, probe-type electrode, that measures the electrical conductance very locally at the occlusal surface, usually in a fissure or pit. The results of studies comparing electrical conductance measurements with other diagnostic systems (e.g., visual inspection, bite-wing radiographs, fibre-optic transillumination) have been very encouraging [White et al., 1978; Flaitz et al., 1986; Rock and Kidd, 1988; Verdonschot et al., 1992]. The specificity of the technique is acceptable and its sensitivity is good, resulting in good predictive values [Verdonschot et al., 1992].

Although encouraging results have been published the diagnosis of caries by measurement of electrical conductance requires further research. As mentioned before, the method uses a scanning technique whereby a separate measurement is required for every site at the occlusal surface, making full mouth examination very time-consuming. It would be preferable if the diagnosis of an entire occlusal surface could be achieved by a single measurement. However, the electrode area at each measurement would then be increased from much less than 1 mm² (the probe tip in the scanning method) to probably more than 5 mm² (occlusal surfaces of premolar or molar teeth). This enlargement of the electrode area in itself will increase the conductance, but to what extent is as yet unclear. A previous study indicated that enamel may act as a normal conductor [Hoppenbrouwers et al., 1986], in that conductance and electrode area are linearly related. This behaviour may compromise the ability of the instrument to discriminate between sound and carious tooth structure when the area of the surface that is being measured is relatively large.

The aim of this study was to determine the influence of the area of the enamel electrode on the conductance of visually sound, smooth enamel in extracted teeth, and to compare the results with the conductance cut-off for dentinal caries as used in the scanning method of electrical caries measurements.

**Materials and Methods**

The teeth used in this study were caries-free premolar teeth extracted for orthodontic reasons. The storage medium was saline. Twenty-five teeth were selected which had complete or virtually complete root formation and visually largely intact buccal surfaces. Immediately prior to measurement, each tooth was removed from the water, blotted dry with tissue paper, and positioned on a wax support. The root of the tooth was covered with electrode gel, also in contact with the reference electrode of the conductance measuring instrument (Electronic Caries Monitor or ECM, P. Borsboom Sensortechnology and Consultancy, Westeremden, The Netherlands). The buccal surface of the tooth was facing a camera. A grey-coloured dentifrice was applied to the buccal tooth surface and the area was enlarged in increments. After each increment a colour slide was taken of the buccal tooth surface together with a metric reference, to be used for area determination. Subsequently, an ECM measurement was taken and the ECM reading recorded. For each tooth 5–10 dentifrice increments were applied and measured, with toothpaste after the final increment covering between 4 and 20 mm². The entire procedure took between 2 and 3 min per tooth.

The colour slides were digitised using a CCD camera and imaging board (Matrox Ltd., Dorval, Que., Canada). The contrast in brightness between the tooth surface and the dark dentifrice allowed for a clear demarcation of the dentifrice area. Using the metric reference on the slide, the area of one pixel was measured and multiplied by the number of pixels of the dentifrice area, according to the method described by Verdonschot et al. [1990].

The ECM reading appears on a display on the front of the instrument. It can lie in a range of about -1.00 to 13.00, representing increasing electrical conductance. The threshold for dentinal caries according to the manufacturer's instructions is about 6.00, if the ECM is used in the normal, scanning method. To be able to calculate the electrical resistance (R) from these readings, the ECM was calibrated using a resistance box. A curve fitting procedure showed a third power relationship between log(R) and ECM reading (fig. 1).
\[
\log(R) = -0.002196 \text{ ECM}^3 + 0.042114 \text{ ECM}^2 - 0.37869 \text{ ECM} + 4.5341
\]

where \( R \) is expressed in kilo-ohm. This relationship was used throughout to convert ECM readings into resistances. Electrical conductance was then calculated as \( 1/R \).

The conductance data were plotted as a function of enamel electrode area, and least squares curve fitting was used to fit straight lines through the data points. These lines represent the theoretical linear relationship between conductance \( (C) \) and area \( (A) \):

\[
C = sA + i
\]

where \( s \) is the slope parameter and \( i \) the intercept. The distribution of both slope and intercept was studied. To determine whether the values of these parameters were influenced by the degree of enamel maturation, the teeth were divided into two groups, one with complete (group C) and one with incomplete (group I) root formation. Mann Whitney's U test was used to determine the significance of differences in slope and intercept between these two groups.

Five teeth out of the sample were sectioned longitudinally, to investigate the influence of enamel thickness. However, for each tooth the enamel thickness as covered by the dentifrice in the buccal measurements, varied between about 0.5 and 1.5 mm, and no specific conductivity could be calculated. For the remaining 20 teeth a single electrical conductance measurement of the occlusal surface was performed. The procedure as described for the buccal surface was repeated, but the toothpaste was applied to the occlusal fissure system. A colour slide was also made, for area determination.

### Results

For two teeth the final buccal measurement deviated strongly from the previous ones, in that it showed a markedly increased conductance. Re-examination of the colour slides of the area increments and of the teeth themselves showed small enamel cracks, probably forceps damage at the time of extraction, that were covered by the final dentifrice increment in these two teeth. It was concluded that these cracks probably influenced the conductance, and the measurements were therefore excluded from the curve fitting procedure.

The data plots indicated and the curve fitting procedures confirmed that there was a good linear relationship of conductance vs. area for all 25 teeth, with an \( R^2 \) ranging from 0.88 to 1.00 and a mean \( R^2 \) of 0.97. In figure 2 an example of a typical data plot with fitted line is shown. The values of the parameters for each tooth, however, showed high variability. In figure 3 the ranges (median, hinges and main body of data) of both slope and intercept for the entire group of 25 teeth are shown, and also the ranges of these parameters for groups C and I. The two groups differed significantly in slope values \((p = 0.025)\). No significant difference in intercept values was found between groups C and I \((p = 0.78)\).

Figure 4 shows the 25 fitted lines, extrapolated if required to an area of 15 mm², along with a horizontal line representing the conductance threshold for dentinal caries in the scanning method. The teeth in group I are identified by dotted lines. The two measurements that were excluded...
from the curve fitting procedures are also indicated in figure 4. The first tooth to reach the threshold does so at an electrode area of about 7 mm$^2$. Six teeth reach the threshold much earlier than the rest, for which the minimum area of reaching the threshold is about 12 mm$^2$.

Figure 5 shows the electrical conductance of the occlusal surfaces of 18 teeth, as a function of electrode area (2 measurements were excluded, because of the presence of sealants in these teeth). The fitted lines for the 6 teeth that first reached the ECM reading = 6.00 threshold are added. Fifteen measurements in an area range of 5–10 mm$^2$ are all below the threshold. The three data points that lie above the threshold are not from the group of 6 teeth.

**Discussion**

The validity of electrical conductance measurements in caries diagnosis has been studied both for in vitro measurements [Flaitz et al., 1986], for in vivo measurements with validation after extraction of the teeth [Rock and Kidd, 1988; White et al., 1978] and for in vivo measurements with limited preparation of the teeth as a validating method [Verdonschot et al., 1992]. From these studies it appears that the validity of electrical conductance measurements as a diagnostic technique in caries detection is good. There is as yet only one study in which conductance measurements taken in vivo were directly compared to those taken in vitro [Kawaguchi et al., 1972]. The authors reported no significant difference between in vivo and in vitro measurements. The results from the studies mentioned above hence indicate that the in vitro set-up is a good model for in vivo measurements.

The two measurements that were not used in the curve fitting procedures were data points deviating from their own series. Figure 4 shows that they are also slightly high for their electrode area, when considering all series. The high conductance at these measurements was thought to be caused by enamel cracks, probably introduced during extraction. The other teeth, upon re-examination, showed no cracks covered by toothpaste. In pilot studies to this one, the authors always found a high conductance in relation to enamel cracks. It is not clear whether such cracks increase electrical conductance to the same extent as carious involvement does, but if the processes are comparable this would imply that the presence of enamel cracks in vivo may lead to false-positive diagnoses. The same has been put forward for developmental defects in enamel and exceptionally deep fissures [Rock and Kidd, 1988; White et al., 1978]. Although these problems affect scanning and surface measurements alike, the larger the area measured, the greater
the probability of including such anomalies in the electrode area. Further research should establish how sensitive the new method would be to such factors.

The linear relationship between conductance and enamel electrode area was confirmed by this study, as all teeth showed a good fit of a straight line to the data. The slope and intercept parameters of this relationship, however, varied considerably. The distribution of the slopes of the relationship was significantly different for teeth with complete and incomplete root formation, with that for completely formed teeth tending to have a narrower distribution and a lower mean (fig. 3). Clinically, this may present a problem. Flaitz et al. [1986] drew attention to the probability of false-positive diagnoses due to the lack of posteruptive enamel maturation in recently erupted teeth. Le et al. [in press] indeed found very high electrical conductance values in recently erupted first and second molar teeth, which appeared to be sound upon visual inspection. Flaitz et al. [1986] suggested that this problem of false-positive diagnoses due to low enamel maturation would be expected to disappear after the teeth had been in the oral environment for 2–3 months. However, all teeth in the present study were in a stage of root formation that would one associate with a period since eruption, and thus an enamel maturation period, of at least 1 year. This suggests that the enamel may take more than 1 year to mature fully.

The conductance threshold for diagnosing dentinal caries when using the ECM in the scanning method, wherein the enamel electrode is about the size of the probe tip, is 6.00, which represents a conductance of approximately 0.5 Mohm⁻¹ (R = 2 Mohm). Figure 4 shows that this threshold can certainly be passed when measuring larger surfaces of sound enamel. Already at an electrode area of about 7 mm² one of the teeth in this sample had an ECM reading of 6.00. There were 6 teeth in the sample for which the cut-off was reached at a substantially smaller electrode area than for the rest. Three of these are outliers with respect to their intercept (fig. 3), 2 from group C and 1 from group I. No explanation for this phenomenon could be found, although 1 of these teeth had a highly polished buccal surface. The other 3 were not identified as outliers, but they were teeth with incomplete root formation (group I), and slope values that would have been outliers in the group with complete root formation. The critical area of 7 mm² will be easily reached in occlusal surface measurements, particularly in molar teeth. In a previous study Verdonschot et al. [1995] measured electrode areas on occlusal surfaces of premolars and found a range of 5–15 mm². In the present study the occlusal electrode area did not exceed 10 mm² (range: 5.4–9.7 mm²). In neither study limiting the electrode area was tried, and a further reduction seems to be possible. However, due to the uneven nature of the occlusal surface, the true area of enamel covered by conducting medium will be larger than its two-dimensional projection which is measured. Also, for molar teeth the area will be larger. There is no information available as yet about the conductivity of fissure enamel, in relation to that of buccal enamel. Normally, fissures do contain sites where the enamel is significantly thinner than on smooth surfaces. This will positively influence conductivity, although perhaps not as much as would be expected from the relative thickness, as it has been shown that the outer layer of enamel (±100 µm) has a much lower conductance than deeper layers [Hoppenbrouwers et al., 1988]. A combination of all these theoretical considerations leads one to expect that electrical conductance measurements of the occlusal surface of a tooth, with the area covered measured as the two-dimensional projection of the conducting medium, will be higher than for a similar area on the buccal surface.

The results of the occlusal surface measurements are therefore surprising. Although eight measurements (including those above the threshold) were indeed higher than would be expected from the buccal measurements, four were the same, and six were actually lower, these being the same teeth that were identified before as reaching the ECM threshold earlier than the rest of the sample, for buccal measurements (fig. 5). An explanation for this may be that there were specific factors present in the buccal enamel surface, which raised conductance and which did not apply to the occlusal surface. Analogous to the macroscopical cracks that were thought to cause the deviating data points mentioned before, the buccal enamel of these teeth may have incorporated microcracks, invisible to the naked eye and more limited in their effect on conductivity. A longer intraoral period of occlusal enamel than buccal enamel, and a resulting higher maturation level, may have played a role as well. Only 3 out of 18 teeth showed an ECM reading well above 6.00. No histologic validation of the presence of carious lesions was performed in this study, but carious involvement should not be ruled out (fissure staining was present in these 3 teeth). In general, the results are encouraging and seem to indicate that occlusal surface measurements in premolar teeth may be feasible.

However, the area may still present a problem in the practical application of conductance measurements for detecting occlusal caries, especially for molar teeth. Raising the threshold for diagnosing dentinal caries through surface conductance measurements (for instance to ECM reading = 8.00 or 10.00) seems to be a likely solution. An even higher conductance threshold (corresponding to an ECM reading
of about 12.00) has been proposed by Suzuki [1981]. The optimal threshold could perhaps vary, depending on whether it is used for premolar or for molar teeth. Such a measure would certainly reduce the number of false-positive results. This does raise the question, however, whether the instrument will remain sensitive to the change in conductance which is caused by a small carious lesion within a large sound surface. This could compromise sensitivity. Further research should be aimed at determining the optimal conductance thresholds for this method when measuring premolars and molars, and subsequently determining the sensitivity and specificity of the new technique.

**Conclusions**

It was concluded that there is a linear relationship between electrical conductance and the electrode area on sound, smooth enamel in extracted teeth. If the electrode area is sufficiently large the sound enamel may reach conductance levels above the threshold for dentinal caries, that is advocated when using the scanning method. Therefore it was concluded that surface measurements require an area-dependent threshold, which may influence sensitivity and specificity of the new method. Further research should be aimed at determining the optimal thresholds for occlusal measurements in premolars and molars, and the validity of the resulting technique.

**References**


