Evaluation of the accuracy and reproducibility of a replication technique for the manufacture of electroconductive replicas for use in quantitative clinical dental wear studies.

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Summary

This work sought to evaluate the accuracy and reproducibility of a replication process that formed electroconductive replicas from addition cured silicone impressions for the purposes of monitoring tooth surface loss. Replicas were constructed by painting the surface of impressions with one of three high silver content electroconductive paints (Electrocure (EC), RS Silver Paint (SP) and Electrolube (EB)) and, once dry, backing this up with a cyanoacrylate based gel material (Zapit) and die stone. For each paint an impression was recorded of a gauge block of known step height (1270 μm) and five impressions of the palatal surface of a laboratory standard maxillary central incisor were also recorded. All impressions were taken using an addition cured silicone impression material (President). The resultant electroconductive replicas were mapped using a computer controlled probe. This data was analysed to determine both the replica's step height and, using surface matching techniques, the reproducibility of the replication process. The mean step heights recorded were; EC = 1268.43 (SD = 12.09), SP = 1267.09 (SD 1.77) and EB 1299.58 (SD 14.47). Both EC and SP recorded the step height to within 3 μm. In the repeat replication of the palatal surface of an upper central incisor SP maintained a greater constancy of surface topography (99.6 %) that was statistically superior to both EC ($P < 0.05$) and EB ($P < 0.01$). SP was therefore the preferred paint for this technique. Bearing this in mind the replication technique was both accurate and reproducible but vigilance, as to the selection of paint for the process, should be exercised so as not to affect the good accuracy and reproducibility of the technique.

Introduction

Tooth surface erosion is a condition that, according to the 1993 National Survey of Child Dental Health in the United Kingdom (O'Brian, 1994), affects just in excess of half of 5-6 year olds and nearly one quarter of 11 year old children. Monitoring accurately its progression, in order to determine the success or otherwise of preventative measures (such as lifestyle changes) is complicated by the lack of fixed intraoral reference points from which to make measurements. A potential solution, reported previously (Chadwick *et al*., 1997) is to record addition cured silicone impressions of the dentition at different epochs. These facilitate fabrication of electroconductive replica's suitable for mapping, by means of a computer-controlled probe. The resultant maps, termed Digital Terrain Models (DTM's), may be compared using a Surface Matching and Difference Detection Algorithm (SMADDA). This technique mathematically seeks regions of coincidence and conflict between DTM's of the same tooth, at different epochs, to determine the degree of surface loss that has occurred (Mitchell and Chadwick, 1998). A major factor determining the success of such an approach however, is the replication process itself. This should be evaluated in the context of the scenario in which it is applied

The use of replica's, formed from impressions recorded in addition cured silicone, with an electroconductive surface has previously been shown to yield dimensionally accurate replica's suitable for quantitative surface analysis (Lambrechts et al., 1981, 1984, 1989). This technique has been successfully employed, together with a mapping technique, to quantify the *in vivo* wear of both posterior dental restorations (Lambrechts et al., 1984) and human enamel (Lambrechts et al., 1989). An inconvenience of the replication technique described by these workers however, is the time required to electroplate the dental impressions prior to casting the replicas and the need for specialised equipment. The method evaluated in the present work replaces the electroplating process with the brush application of electroconductive paint to the impressions surface prior to casting. This offers the potential to eliminate the need for specialist equipment and shorten the time scale for replica production.

It was the aim of this work therefore to utilise both the computer-controlled probe and SMADDA to evaluate the accuracy and reproducibility of the replication process itself and, in so doing, evaluate the suitability of three potential electroconductive paints for making such replica's.

Materials and methods

These may best be described under the subheadings of replica reproducibility and replica accuracy. In conducting these however, a note was also kept relating to any concerns regarding the handling characteristics of the various paints used in the process of replication.

Replica reproducibility - A plastic permanent maxillary left central incisor (Frasaco, Franz Sachs 410, Germany), intended for phantom head exercises, was mounted using a light curing special tray material (Triad, DeTrey Dentsply, Surrey, UK) upon a circular flat aluminium disc of 53 mm diameter. This was arranged in such a way that, when viewed from above, the palatal surface was uppermost and clearly visible. A special tray was fabricated with 3 mm tray spacing, using the same custom tray material as used to mount the central incisor, to enable impressions of the palatal surface to be recorded. A total of 15 impressions of the central incisor were recorded using this. For each one tray adhesive (Universal Adhesive, Bayer Dental, Germany) was applied to the fit surface of the special tray and allowed to dry. An addition cured light bodied silicone impression material (President, Coltene, Switzerland) was, with the aid of the manufacturers mixing tip, applied to both the mounted tooth’s palatal surface and fit surface of the tray. Following seating of the tray upon the tooth, and the subsequent setting of the impression material, excess set impression material was trimmed away from the external surfaces of the tray with a scalpel. The impression was then withdrawn from the tooth and inspected closely for surface imperfections. If imperfections were present the impression was rejected and retaken.

Each satisfactory impression was allocated to one of three replication groups. Thus, each group contained five impressions. Each group was allocated a high silver content electroconductive paint as detailed in Table I. This was applied, using a brush, to the surface of the silicone impression. Once dry a further coat of paint was applied and two hours later a layer of a cyanoacrylate based gel material (Zapit®, Dental Ventures of America Inc., USA) was applied to back up the painted surface and reinforce it. This was chemically hardened according to the manufacturer’s instructions. In order to increase the thickness of the resultant replica, to facilitate both handling and mounting upon the mapping device, this was further backed up with die stone (Miles Dental Products, South Bend, IN, USA), mixed according to the manufacturer’s recommended powder: liquid ratio, before being removed from the impression. Thus, upon removal from the impression, an electroconductive replica resulted whose surface was composed of a layer of silver paint conforming to the surface dimensions of the tooth under investigation as captured by the impression.

Each replica was transferred to the mapping device that was a development of that described by Chadwick et al. (1997). It had been manufactured by the Medical Physics Department of Ninewells Hospital, Dundee, UK to BS EN ISO 9001 (1994) and consisted of a precision x, y table (Daedal, Pittsburgh, USA) motorised by the addition of two computer controlled stepper motors (RS Components Ltd., Corby, UK) that controlled precisely the position of the table in the horizontal x, y planes. In addition, a third geared stepper motor under computer control, mounted perpendicular to the motorised table, governed the position of an electrical probe relative to the specimen. The probe was manufactured from tungsten carbide wire of 125 μm diameter (Clark Electromedical, Pangbourne UK) and formed part of a feedback loop such that on coming into close proximity with an electrically conductive specimen, wired into the specimen chamber on the x, y table, it ceased its downward travel in the z direction and retracted 50 μm before moving on to the next measurement point. All such data was computer logged and, to minimise the effects of backlash in the stepper motors, measurement was only undertaken when the stepper motors were driving the stage in the positive x and y directions. The positioning and measurement resolution in the x, y and z planes was ± 2.5 μm. Throughout this work the x and y intervals, at which the elevation (z co-ordinate) of the replica was determined, were set at 150 μm.

The resultant data files for each replica type, that comprised a series of Digital Terrain Models (DTM's) consisting of many x, y and z-co-ordinates (generally around 50 x 50 points in size (150 μm apart) giving 2,500 data points in all within a grid of 7.5 mm x 7.5 mm) for each replica were then compared using a SMADDA. This utilised a least squares approach to surface matching in which the surfaces being compared were moved mathematically so that the surface of one DTM was superimposed upon that of another for comparative purposes. To this end each surface model was described by a set of Cartesian co-ordinate triplets, i.e. a set of (x, y, z) values. The two sets of co-ordinates represented the same original surface as replicated on different occasions. The sum of squares of the surface separations in the vertical direction of these points was minimised in the solution. Making initial estimates of the various parameters required to implement this namely; rotations and translations about x, y and z of the DTM's achieved this. Further continuous refinement of these parameters ensued until the vertical separations between the DTM's were minimised. Full accounts of the mathematics involved in this procedure are given in Mitchell and Chadwick; 1998 and 1999. In summary however, the fundamental aim of the procedure is to find that spatial relationship between the co-ordinate systems, which brings the surfaces into closest co-incidence. To achieve this end those points at which the separation was greater than a pre-defined quantity (set at 150 μm for this work), at which obvious distortion was defined for the purposes of the program to occur, were excluded to facilitate the superimposition process. Once the co-ordinate systems were approximated however, these points were then included in the final wear analysis with the degree of constancy, or otherwise, across the replica series of each paint being expressed as the mean overall percentage of the surface to remain unchanged. In addition, as a finer indicator of the repeatability of both the replication and surface matching process combined the mean Root Mean Square (RMS) of the surface matches was also calculated according to the method previously described (Mitchell and Chadwick; 1998, 1999). For each replica type a total of 20 surface matches were conducted. This included both forward (e.g. replica 1 versus 2) and reverse matches (e.g. replica 2 versus 1).

Replica accuracy – To determine the accuracy of the replication process two engineers gauge blocks (Matrix Gauge Blocks, Coventry Gauge Ltd., Leicester, UK) of precisely known thickness were wrung together to form a step height of 1270 μm. Three separate impressions of this arrangement were recorded in the light bodied addition cured silicone impression material President, with the aid of a tray adhesive and special tray, as previously described. Once set the impression was removed and closely inspected for surface defects. Satisfactory impressions were used to fabricate an electroconductive replica using one of the three electroconductive paints (Table I) as described under the subheading replica reproducibility. The resultant replica's were transferred to the mapping device in order to determine the step heights of the replica's. This was determined at 13 separate sites measuring from the base of the step to the top over a horizontal distance of 12 mm. For each paint type the mean step height and standard deviation of the observation was then calculated.

Results

In relation to the handling characteristics all of the electroconductive paints were easy to apply and acceptable to the operator. Electrolube did not however, provide a sufficiently durable coating that was amenable to repeated mappings of the same replica.

Table II summarises for each paint the mean percentage area of the palatal surface that was unchanged across the series of five replica's. The standard deviations of these observations together with the mean RMS of the surface matches are also given in this table. This latter parameter gives an indication of the closeness of fit of the surface matches and includes the surface matching error attributed to both the surfaces being compared. As a result, the error that can be attributed to one surface is also given in this table.

Analyses of variance to compare the performance of each replica type according to the parameters of the mean percentage area of the palatal surface that was unchanged and the root mean square of the surface matches revealed highly statistically significant differences ($P < 0.001$). Localisation, by Tukey Comparison of Means tests, indicated that in terms of the mean percentage area of the palatal surface that was unchanged RS Silver maintained a greater constancy of surface topography (99.6 %) that was statistically superior to both electrocure ($P < 0.05$) and RS Electrolube ($P < 0.01$). In addition, the replicas constructed from RS Silver Paint gave highly statistically significantly ($P < 0.01$) lower mean RMS values for the surface matches compared to all the other paints tested.

Table III contains the mean values obtained for the step height of the replica's fabricated using the three different paints. This height was known to be 1270 μm. As well as the mean height the Standard Deviation of the observations is also included together with the mean error of the measured step height in microns. An analysis of variance of the mean step heights highlighted highly statistically significant differences ($P < 0.001$). RS silver paint and Electrocure did not differ significantly ($P > 0.05$) (Students t Test) but Electrolube gave a statistically significantly greater ($P < 0.001$) (Students t Test) step height than both these materials. Both Electrocure and RS Silver paint gave replicas that were within 3 μm of the original test piece.

Discussion

This investigation sought to assess the accuracy and reproducibility of the fabrication of electroconductive replica's for the purpose of monitoring tooth surface loss. These formed part of a previously reported integrated system for monitoring tooth and restoration wear (Chadwick et al., 1997).

The use of President™ addition cured silicone elastomeric impression material, as used in the present study, has been reported previously in a favourable light (Lambrechts et al 1981, 1984). Unlike the technique reported here however, the silicone impression was electroplated with copper prior to casting the replica. The disadvantages, however, of electroplating are the time to accomplish the process and the need for specialised equipment. In contrast, the pre-treatment of silicone impressions with a silver paint, as reported here, offers the potential to speed up the process, essential in any large scale clinical study employing the technique, and does not require expensive equipment. Any novel replication method therefore must demonstrate an accuracy of a least the same degree, if not better, of already recognised techniques.

It is of interest to note that although the literature contains a plethora of reports upon the dimensional accuracy of impressions much of this information has been derived by comparing the dimensions of a standard test object to replica's cast from the impressions themselves (Bloem et al., 1991; Price et al., 1991 and Nissan et al., 2000). As a result of this experimental design it is not possible to determine how much dimensional change arises from either the impression or casting procedures in their own right. It has however, been demonstrated that the production of die stone replica's (impression and casting) results in a dimensional change of no more than 9 μm (Price et al., 1991) for the entire replication process. It is this combined figure that is of relevance to the scenario of this work.

In terms of reproducibility both Electrocure and RS Silver Paint replicas gave values of the mean percentage surface unchanged approaching 100 % in a repeat series of replications (Table II). The subsequent statistical analysis however, demonstrated that in this respect RS Silver paint was the superior product. This was further borne out by the lower mean RMS values, attributed to one surface, observed for the surface matches of replicas constructed of RS Silver Paint (26.41 μm) as compared to those of Electrocure (37.20 μm). It should also be borne in mind that this parameter, as well as indicating the closeness of the surface matching, also gives an indirect assessment of the quality of the replica surface. It is also pleasing to note that the observations on the accuracy of these materials (Table III) reinforce these findings. Although, in this regard, RS Silver Paint gave a slightly greater error (Error 2.91 μm) in step height reproduction than Electrocure (Error 1.57 μm), that was statistically not significant ($P > 0.05$), it may still be prudent to adopt RS Silver as the preferred replication material due to the greater variation in step height reproduction as illustrated by the relatively high standard deviation of the electrocure (SD = 12.09) observations compared to those for RS Silver Paint (SD = 1.77). In addition, it could also be argued that this greater variability would influence the reproducibility of a repeat series of replicas made from this material. This would impact upon the mean RMS of any surface matches carried out and would certainly explain the higher RMS values seen in this study (Table II) for the replicas fabricated from Electrocure. As a result it would seem prudent to eliminate this potential additional source of error by using RS Silver Paint as the material of choice.

In contrast to the results for RS Silver Paint and Electrocure those for Electrolube are disappointing with both poor accuracy (Table III) and reproducibility (Table II) being demonstrated. An explanation for this behaviour lies in the inclusion of acrylic resin (manufacturers data) in this material. This ingredient is apparently absent from the other two materials as no reference to its inclusion is made in the associated materials safety data sheet. Acrylic resin is associated with a marked shrinkage on polymerisation (McCabe and Walls, 1998) and this would both distort the painted surface and account for this materials relatively poor performance in the replication process.

For both replicas constructed of RS Silver Paint and Electrocure the good reproducibility and accuracy of less than 3 μm represents an improvement upon die stone replicas. This indicates an advance over the accuracy reported for die stone replicas (Price et al., 1991). For both RS Silver Paint and Electrocure the dimensional error, expressed as a percentage of the actual step height (0.12 % and 0.23 % respectively), lies well within the permissible limits for the 24 hour dimensional change of Type 3 elastomeric impression materials (0 – 1.5 %) as specified in ISO 4823.

It should also be pointed out that the scenario in which the replication technique is used is to monitor the progression, or otherwise, of tooth surface loss from one epoch to another. It is therefore considered by some of no great importance if the replication process suffers small dimensional change providing this is reproducible from one sample to another, since it is a difference in contour rather than absolute values that are of interest (Williams et al., 1983). Notwithstanding this comment however, the replication technique evaluated here is both straightforward, accurate and reproducible. Care must however, be exercised in the selection of paints for the process as these can affect markedly the good accuracy and reproducibility that the technique offers.

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Table I

The Electroconductive Paints used in the Study

Product	Manufacturer
Electrocure	Comma, Gravesend, Kent, UK.
RS Silver Paint	RS Components, Corby, Northants, UK.
RS Electrolube	RS Components, Corby, Northants, UK.

Table II

The Mean % of the Palatal surface that was unchanged in repeat replications of the same tooth and mean RMS of the Surface Matches.

Paint	**(A) Mean % of Surface Unchanged (S.D. (n))**	**(B) Mean RMS of Surface Matches (μm) (S.D.)**	**(C) Proportion of RMS attributed to one surface (B/square root 2)**
Electrocure	99.25 (0.46)	52.60 (3.52)	37.20
RS Silver Paint	99.61 (0.37)	37.34 (4.48)	26.41
RS Electrolube	97.26 (0.86)	42.30 (3.03)	29.92

Table III

The Mean Step Height, Standard Deviation and Error of Replicas fabricated using Three Electroconductive Paints compared to the Original Test Piece Step Height of 1270 μm.

Paint	**Mean Step Height (μm)**	**Standard Deviation**	**Overall Mean Error**
Electrocure	1268.43	12.09	- 1.57
RS Silver Paint	1267.09	1.77	-2.91
RS Electrolube	1299.58	14.47	29.58