THE CAVITY SEALING EFFICIENCY OF COMPOSITE RESIN AND SILICATE CEMENT RESTORATIONS: ITS RELATIONSHIP TO MICROPENETRATION BY RADIOACTIVE TRACERS

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INTRODUCTION

The necessity for a close adaptation between a restoration and the adjacent tooth structure under oral conditions has long been recognised. In 1908, Black\(^{(14)}\) indicated that two factors of primary importance in a dental restorative material were "adaptability to the walls of cavities, (and) freedom from shrinkage and expansion after having been made into fillings". Conceivably, an ideal restorative material would adapt completely to the walls of a cavity and have a similar coefficient of thermal expansion to that of tooth structure so that, under all conditions, particulate matter or deleterious products from the oral environment would be prevented from penetrating between the restoration and the adjacent cavity walls. To date, no permanent restorative material possesses these properties, however research is continuing in an effort to develop a permanent restorative material that will adhere to the walls of a cavity\(^{(2)(28)(81)}\).

Assessments of the cavity sealing efficiency of dental restorations have been based on the ability of bacteria\(^{(36)(46)(69)(86)(94)}\), air under pressure\(^{(33)(82)}\),
dyes* or radioactive tracers† to penetrate between a restoration and the adjacent cavity walls. In studies where dyes or radioactive tracers were used, the degree of micropenetration‡ or marginal penetration by the tracer, was taken as an indication of the cavity sealing efficiency of the restoration under investigation.§

In recent years the first products resulting from the search for an adhesive restorative material have become available. These materials, termed composite restorative resins, can be used in situations where silicate cement or acrylic resin would otherwise be used. Docking(28) has indicated that composite restorative resins do not consist entirely of a resin.

‡ The term micropenetration is used in this study to denote tracer, particulate matter or fluid penetration along the tooth-restoration interspace and into the dentine subjacent to the restoration. The term marginal penetration is used to denote tracer, particulate matter, or fluid penetration along the tooth-restoration interspace, while dentine penetration is used to denote tracer, particulate matter or fluid penetration into the dentine subjacent to the restoration.
§ This does not apply, however, to studies in which the test restorations were placed in glass tubes(46)(62) or epoxy resin cups (44), instead of being placed in cavities prepared in tooth structure.
or copolymer but contain a high proportion (70 to 80 per cent) of inorganic material to control the optical, thermal and strength properties of the material. An evaluation of the physical properties of three such materials* by Macchi and Craig(61) showed that each material had a higher modulus of elasticity, yield strength, compressive strength, tensile strength, and shear strength than acrylic resin†, as well as having less polymerisation shrinkage and a lower coefficient of thermal expansion than acrylic resin.

Studies of the cavity sealing efficiency of restorations made from some of the longer established restorative materials, such as amalgam, silicate cement and acrylic resin, have shown that the degree of tracer penetration along a tooth-test restoration interspace (marginal penetration), or the degree of tracer penetration along a tooth-test restoration interspace into the subjacent dentine (micropenetration), may be modified by one or more of the following factors:

(i) Aging in vivo(40)(60)(80)(112), or


* Addent 35, Addent 12 (3M Company, St. Paul, Minnesota.) and Dakor (L.D. Caulk Company, Milford, Delaware.).
† Sevriton (Amalgamated Trade Distributors Ltd., London, W.1.).
‡ In this study, the description cavity linings applies to both the film type liner and the cement type base.
(iii) Temperature changes (thermal cycling)\(^{(17)(22)}\)\(^{(37)(43)(52)(77)(83)(94)(101)(110)}\).

However, as far as can be ascertained from the literature, only a limited amount of work has been done on the effect of aging and cavity linings on the marginal penetration, or micropenetration, of composite resin restorations. Studies on the effect of aging\(^{(43)(77)(103)}\) were conducted entirely in vitro, while studies on the effect of cavity linings\(^{(30)(43)(110)}\) were limited to the investigation of one type of lining, a vinyl copolymer dissolved in acetone\(^{(96)*}\). Although composite resin is a possible substitute for the widely used anterior restorative material, silicate cement\(^{†}\), only two comparisons of the cavity sealing properties of composite resin and silicate cement have been made\(^{(43)(103)}\), and both studies were conducted entirely in vitro.

The purpose of this study was to investigate the influence of three factors, aging, cavity linings and thermal cycling, individually and in combination, on the micropenetration of composite resin and silicate cement restorations placed in vivo. Tracers of ionic dimensions, such as radioisotopes, were considered more suitable for this study than were larger tracers such as dyes,

\* Addent Cavity Liner (3M Company, St. Paul, Minnesota).

\† An estimated 50 million silicate cement restorations are placed annually\(^{(89)}\).
Or bacteria (Appendix 1). Because of their smaller size, tracers of ionic dimensions should have the potential to detect smaller spaces between a restoration and the adjacent tooth structure than dyes or bacteria. However, not all radioactive tracers of ionic dimensions are capable of penetrating a tooth-restoration interspace with equal facility\(^{(39)}\), therefore, an initial investigation was made to determine which of five different radioactive tracers had the properties most suitable for investigating the cavity sealing efficiency of composite resin and silicate cement restorations. A report of this preliminary study is incorporated in this thesis.

Following the preliminary study and the choice of a satisfactory tracer, the in vivo investigation was carried out using dogs as the experimental animals.

This thesis presents a comprehensive review of the literature relating to the radioactive tracer assessment of the cavity sealing efficiency of composite resin and silicate cement restorations, a description of the methods used in the study, an analysis of the results obtained, and a discussion of the significance of the experimental findings in relation to the problem of micropenetration.
REVIEW OF LITERATURE

The earliest report on the use of radioactive tracer techniques for the assessment of the cavity sealing efficiency of dental restorations was made by Armstrong and Simon (1) in 1951. They used calcium-45 as tracer to test the cavity sealing efficiency of one silicate cement, one amalgam, one gold inlay, one gold foil, one zinc phosphate cement and three acrylic resin restorations placed in Class V cavities prepared in extracted human teeth. Their autoradiographic findings showed that $^{45}\text{Ca}$ was able to penetrate to some degree along the tooth-restoration interspace of each of these restorations within a period of 48 hours. In the same year Wainwright (107), in a report on the penetration of enamel by the radioactive salts of calcium, copper, palladium, plutonium, silver and zinc, mentioned that $^{45}\text{Ca}$ had penetrated along the entire tooth-restoration interspace of an old silicate cement restoration present in one of the extracted teeth used in his experiment.

1. METHODS USED IN THE RADIOACTIVE TRACER ASSESSMENT OF THE CAVITY SEALING EFFICIENCY OF SILICATE CEMENT AND COMPOSITE RESIN RESTORATIONS

Armstrong and Simon (1) used autoradiography* to

* Autoradiography is a method of detecting radioactive tracers based on the ability of the emitted radiation to affect the silver halide crystals of a photographic emulsion. The section containing the radioactivity is ... (continued on page 7)
detect and locate radioactivity within sections prepared through the restorations and the surrounding tooth structure. Their assessment of the cavity sealing efficiency of the test restorations was based on the depth of radioisotope penetration that had occurred along the tooth-restoration interspace during the period that the tooth-restoration margins had been exposed to the radioisotope solution. In the subsequent micropenetration studies on silicate cement and composite resin restorations, assessments of the cavity sealing efficiency of these restorations were also made, partially or completely, from the depth of marginal penetration seen in autoradiographs from sections prepared through the restorations and the adjacent tooth structure \((3)(30)(39)(40)(43)(50)(64)(72)(77)(80)(101)(102)(110)(112)\). The basic steps of the autoradiographic technique common to these studies were:

(i) **Exposure of the restorations to a radioactive tracer solution.** This was done by immersing extracted teeth with the test restorations in

(continued from page 6) ... placed firmly in contact with a photographic film (such as dental x-ray film) and left in the dark for an appropriate period. On the subsequent development of the film a picture known as an autoradiograph is obtained. The darkened areas on the film correspond to the areas in the section in which the radioisotopes have localised.
situ in a radioactive tracer solution* for a predetermined period. However in the case of two in vivo micropenetration studies on silicate cement restorations, methods were used whereby the surfaces of the restorations and surrounding tooth structure were exposed to radioactive tracer solutions while still in situ in the mouths of the experimental animals (50)(112).

To prevent tracer penetration through enamel defects and root structures, and also to restrict tracer penetration to areas adjacent to tooth-restoration margins, coatings of wax (1)(3)(43), nail polish (110), a combination of nail polish and wax (112), or a combination of nail polish and tin foil (64)(72)(77)(80)(101)(102) were used to seal the root surface and areas of the enamel surface.

(ii) Preparation of sections through the restorations and surrounding tooth structure. In 1951, Armstrong and Simon\(^1\) prepared horizontal tooth-restoration sections for autoradiography, however, as far as can be ascertained from the literature the subsequent workers used longitudinal sections for this purpose.

(iii) Placing of sections in contact with a photographic emulsion to produce survey autoradiographs. Dental x-ray film\(^{(1)(3)(39)(40)(43)(64)(72)(77)(80)(101)(102)}\) and photographic film\(^{(110)(112)}\) were used for autoradiography.

In 1956, Crawford and Larson\(^{26}\) indicated that they had investigated the possibility of using nuclear track plates* for the autoradiography of tooth-restoration sections containing calcium-45. However the short shelf life and long exposure times necessary to produce autoradiographs with the most suitable nuclear track plates available at that time contra-indicated their use for this purpose. Kapsimalis, Evans and Tuckerman\(^{56}\) in 1965, found that the use of emulsion coated glass

* Nuclear track emulsions have amongst other features small grain size which enables autoradiographic images of high resolution to be produced.
plates* for the autoradiography of tooth-restoration sections containing sulphur-35 gave an image of better resolution than that obtained with dental x-ray films†, although longer exposure times were needed with the emulsion coated glass plates to secure the best results.

One problem with the autoradiography of tooth-restoration sections using the contact method has been the difficulty of relating the autoradiographic image to the underlying tooth structure. In 1961, Going, Massler and Dute\(^{(41)}\) reported details of a technique in which tooth-restoration sections in contact with x-ray films were exposed to roentgen rays after the autoradiographic exposure period, so that, when the emulsion was processed, a reference outline of the tooth-restoration section was superimposed over the autoradiographic image.

With one exception, the autoradiographic technique has been the principle method used in the radioactive tracer assessment of the cavity sealing efficiency of

* Kodak Autoradiographic Plates, Type A, and Kodak black and white photographic emulsion coated glass plates.

† Minimax Extra Fast Double Coated X-Ray Film, Kodak Ultra-Speed X-Ray Film, and Rinn Hyper-Fast X-Ray Film.
silicate cement and composite resin restorations. The one exception was the study by Yen\textsuperscript{(112)} who used a topographical sampling technique to measure the amount of radioisotope uptake (i) within the body of silicate cement, zinc phosphate cement and amalgam restorations, and (ii) in the tooth structure adjacent to these restorations. Yen only used autoradiographs to supplement his findings.

Details of the experimental methods used in the radioactive tracer assessment of the cavity sealing efficiency of silicate cement and composite resin restorations are presented in Table 1.

Although Brännström and Söremark\textsuperscript{(17)} did not investigate the cavity sealing efficiency of either silicate cement or composite resin restorations, their study is of particular interest because of the methods they used to reduce some of the experimental variables inherent with in vivo micropenetration studies. They, (i) carefully standardised their cavity preparations and other aspects of the operative procedures, (ii) only selected contra-lateral teeth for cavity preparation, using one tooth for the placement of the control restoration and the other tooth for the placement of the test restoration, and (iii) selected patients within a narrow age grouping (10 to 18 years).
<table>
<thead>
<tr>
<th>AUTHOR</th>
<th>SPECIES, TYPE AND OTHER DETAILS OF TEETH USED IN EXPERIMENT</th>
<th>TYPE, POSITION AND SIZE OF CAVITY PREPARATION</th>
<th>DETAILS OF RADIOACTIVE TRACER SOLUTION</th>
<th>DURATION OF SPECIMEN EXPOSURE TO RADIOACTIVE TRACER</th>
<th>AUTORADIOGRAPHIC DETAILS</th>
<th>OTHER RESTORATIONS TESTED UNDER SIMILAR CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Armstrong and Simon(1)</td>
<td>Sound extracted lower 2nd bicuspid teeth.</td>
<td>Class V Cavities. prepared in buccal surfaces.</td>
<td>$^{45}$Ca Cl$_2$ - specific activity 80 MC per gram Ca.</td>
<td>48 hours</td>
<td>X-ray film</td>
<td>Not stated</td>
</tr>
<tr>
<td>Barber and Massler(3)</td>
<td>Extracted human teeth.</td>
<td>Class V cavities.</td>
<td>(i) $^{45}$Ca Cl$_2$ - specific activity 20 microcuries per ml. pH 2.8. (ii) Na$_2$SO$_4$ - specific activity 20 microcuries per ml. pH 2.8.</td>
<td>24 hours</td>
<td>Fast dental x-ray film.</td>
<td>(i) 48 hours</td>
</tr>
<tr>
<td>Going, Massler, and Dute(39)</td>
<td>Extracted human teeth from patients of average age 45 years.</td>
<td>Class V cavities prepared in sound gingival sections of facial and lingual surfaces.</td>
<td>(i) $^{22}$Na Cl - 10-15 microcuries per ml. pH 5.2-6.0 (ii) $^{45}$Ca Cl$_2$ - 20 microcuries per ml. pH 5.2-6.0. (iii)Na$_2$SO$_4$ - 20 microcuries per ml. pH 5.2-6.0.</td>
<td>24 hours</td>
<td>Fast double coated dental x-ray film</td>
<td>(i) 6 hours</td>
</tr>
<tr>
<td>AUTHOR</td>
<td>SPECIES, TYPE AND OTHER DETAILS OF TEETH USED IN EXPERIMENT</td>
<td>TYPE, POSITION AND SIZE OF CAVITY PREPARATION</td>
<td>DETAILS OF RADIOACTIVE TRACER SOLUTION</td>
<td>DURATION OF SPECIMEN EXPOSURE TO RADIOACTIVE TRACER</td>
<td>AUTORADIOGRAPHIC DETAILS</td>
<td>OTHER RESTORATIONS TESTED UNDER SIMILAR CONDITIONS</td>
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</tr>
<tr>
<td>Going, Messler and Dute(40)</td>
<td>As above</td>
<td>As above</td>
<td>Na$^{131}$I - specific activity 25-50 microcuries per ml. pH 5.2-6.0.</td>
<td>24 hours</td>
<td>As above. 1 to 24 hours</td>
<td>Gold foil, gold inlay, copper amalgam, copper cement, silver amalgam, zinc oxide-eugenol, temporary stopping, zinc phosphate cement, acrylic resin.</td>
</tr>
<tr>
<td>Going and Sawinski(43)</td>
<td>Extracted human teeth.</td>
<td>Class V cavities prepared in opposing surfaces of each tooth (2 cavities in each tooth).</td>
<td>45Ca Cl$_2$ - specific activity 50 microcuries per ml.</td>
<td>24 hours</td>
<td>As above. Not stated.</td>
<td>Silver amalgam, gold foil, composite resin and acrylic resin.</td>
</tr>
<tr>
<td>Harris(50)</td>
<td>Teeth in situ in a dog.</td>
<td>Not stated.</td>
<td>45Ca</td>
<td>2 hours.</td>
<td>Not stated. Not stated.</td>
<td>Nil</td>
</tr>
<tr>
<td>Menegale, Swartz and Phillips(64)</td>
<td>Extracted teeth.</td>
<td>Simple cavities - 2.5 mm deep and 2.2 mm wide, prepared in facial surfaces.</td>
<td>45Ca Cl$_2$ - specific activity 0.1 milli-curies per ml. pH 5.5</td>
<td>2 hours.</td>
<td>Fast dental 24 hours.</td>
<td>Amalgam, gold foil, mat gold and acrylic resin.</td>
</tr>
<tr>
<td>Norman, Swartz and Phillips(72)</td>
<td>Extracted teeth</td>
<td>Class V cavities prepared in middle third of buccal surfaces.</td>
<td>As above.</td>
<td>As above.</td>
<td>As above 17 hours</td>
<td>Zinc phosphate cement and zinc oxide-eugenol cement.</td>
</tr>
<tr>
<td>AUTHOR</td>
<td>SPECIES, TYPE AND OTHER DETAILS OF TEETH USED IN EXPERIMENT</td>
<td>TYPE, POSITION AND SIZE OF CAVITY PREPARATION</td>
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<tr>
<td>Swartz and Phillips (101)</td>
<td>Sound extracted cuspid and bicuspids teeth.</td>
<td>Class V cavities prepared in incisal third of cuspid teeth. Class I cavities prepared in occlusal surface of bicuspids teeth.</td>
<td>As above</td>
<td>As above</td>
<td>As above</td>
<td>As above</td>
</tr>
<tr>
<td>Swartz and Phillips (102)</td>
<td>As above.</td>
<td>Class I and Class V cavities.</td>
<td>As above</td>
<td>As above</td>
<td>As above</td>
<td>As above</td>
</tr>
<tr>
<td>Yen (112)</td>
<td>(i) Anterior teeth (minus upper lateral teeth) in situ in monkeys. (ii) Extracted upper lateral monkey teeth.</td>
<td>Two Class V cavities prepared side by side in labial surface of each tooth.</td>
<td>$^{45}$CaCl$_2$ - 15 microcuries per ml.</td>
<td>4 hours</td>
<td>Photographic film. (Autoradiography only used as supplement to topographical sampling method.)</td>
<td>Amalgam zinc phosphate cement</td>
</tr>
</tbody>
</table>
### DETAILS OF METHODS USED IN THE RADIOACTIVE TRACER ASSESSMENT OF THE CAVITY SEALING EFFICIENCY OF COMPOSITE RESIN RESTORATIONS

<table>
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<tr>
<th>AUTHOR</th>
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<th>DURATION OF SPECIMEN EXPOSURE TO RADIOACTIVE TRACER</th>
<th>AUTORADIOGRAPHIC DETAILS</th>
<th>OTHER RESTORATIONS TESTED UNDER SIMILAR CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolven and Hampel (30)</td>
<td>Teeth in situ in monkeys</td>
<td>Not stated</td>
<td>$^{45}\text{Ca}$</td>
<td>Not stated</td>
<td>Not stated</td>
<td>Nil</td>
</tr>
<tr>
<td>Going and Sawinski (43)</td>
<td>Extracted human teeth.</td>
<td>Class V cavities prepared in opposing surfaces of each tooth (2 cavities in each tooth)</td>
<td>$^{45}\text{CaCl}_2$ - specific activity 50 micro-curies per ml.</td>
<td>24 hours.</td>
<td>Fast double coated dental x-ray film.</td>
<td>Silver amalgam, silicate cement, gold foil, and acrylic resin.</td>
</tr>
<tr>
<td>Peterson, Phillips and Swartz (77)</td>
<td>Sound extracted human teeth.</td>
<td>Class V cavities.</td>
<td>$^{45}\text{CaCl}_2$ - specific activity 0.1 milli-curies per ml. pH 5.5.</td>
<td>2 hours</td>
<td>Fast dental x-ray film</td>
<td>Acrylic resin.</td>
</tr>
<tr>
<td>Wakely and Hoffman (110)</td>
<td>Extracted human teeth.</td>
<td>Class V cavities prepared in gingival third of surfaces selected as suitable for cavity preparation.</td>
<td>$^{45}\text{Ca}$</td>
<td>5 hours</td>
<td>Photographic 17 hours film.</td>
<td>Nil</td>
</tr>
</tbody>
</table>
Since 1960 there has been a tendency for investigators to follow either one of two experimental approaches to the problem of assessing the cavity sealing efficiency of silicate cement restorations using the autoradiographic technique. A similar difference in experimental approach was also apparent in two of the reports on the cavity sealing efficiency of composite resin restorations published in 1966\(^{(43)}\) (77).

Menegale, Swartz and Phillips\(^{(64)}\), Phillips, Gilmore, Swartz and Schenker\(^{(80)}\), Swartz and Phillips\(^{(101)}\) (102), Norman, Swartz and Phillips\(^{(72)}\), and Peterson, Phillips and Swartz\(^{(77)}\) used virtually identical experimental methods in which:

(i) The roots of the extracted teeth, as well as any defects in the enamel surface, were sealed with a combination of nail polish and tin foil. The tooth-restoration margins were left uncovered.

(ii) The specimens were immersed in a \(^{45}\text{CaCl}_2\) solution of specific activity 0.1 millicuries per ml. and pH 5.5 for a period of two hours.
(iii) The specimens were sectioned longitudinally through the restorations and placed on dental x-ray film for 17 hours (although Menegale, Swartz and Phillips used an exposure time of 24 hours).

Only one radioactive tracer, calcium-45 was used in these experiments. Phillips, Gilmore, Swartz and Schenker (80) and Swartz and Phillips (101) indicated that they had selected calcium-45 as tracer on the basis of its use in the earlier micropenetration studies of Armstrong and Simon (1), Sausen, Armstrong and Simon (90) and Crawford and Larson (26).

In each of these studies (64) (72) (77) (80) (101) (102), with the exception of that by Menegale, Swartz and Phillips (64), the findings were qualitative. Menegale, Swartz and Phillips quantified their autoradiographic findings by measuring the area of radioisotope infiltration in the region between the walls of the test restoration and the adjacent cavity walls, and then expressed this measurement as a ratio of the perimeter of the entire tooth-restoration interspace to give a value for the cavity sealing efficiency of the restoration. They did not include any radioisotope uptake in the dentine subjacent to the cavity walls in
their assessment of cavity sealing efficiency, indicating that "Where the radioactive isotope had penetrated the dentinal tubules, these areas were not included, since dentine infiltration is undoubtedly related more to tooth permeability than marginal leakage" (65).

Another experimental approach is seen in the studies of Going, Massler and Dute (39)(40), Barber and Massler (3) and Going and Sawinski (43). In each of these studies, the autoradiographic assessment of the cavity sealing efficiency of a test restoration was based on the depth of marginal penetration and the depth of dentine penetration by the radioactive tracer during a 24 hour immersion period. With the exception of the Barber and Massler (3) study, these findings were quantified using a penetration scale similar to that shown in Figure 2.

Going, Massler and Dute (39) and Barber and Massler (3) used more than one radioactive tracer to assess the cavity sealing efficiency of silicate cement restorations. Going, Massler and Dute had found in preliminary studies that the ionic charge and chemical activity of a radioactive tracer could influence, amongst other factors, its ability to penetrate along the space between a restoration and the adjacent tooth structure.
For this reason, they used three different tracer solutions ($^{45}\text{CaCl}_2$, $^{22}\text{NaCl}$ and $\text{Na}_2^{35}\text{SO}_4$) to test the marginal seal of silicate cement restorations. Barber and Massler used two different tracer solutions ($^{45}\text{CaCl}_2$ and $\text{Na}_2^{35}\text{SO}_4$) because this combination of tracer solutions provided radioactive negatively and positively charged divalent ions. In another study, Going, Massler and Dute (40) selected $\text{Na}^{131}\text{I}$ as tracer to test the cavity sealing properties of silicate cement and nine other restorative materials on the basis of its availability, its half life, its ability to produce fairly detailed autoradiographs and its inertness as a tracer.

The absence of a standardised experimental approach to the radioactive tracer assessment of the cavity sealing efficiency of silicate cement and composite resin restorations is reflected in some of the conflicting findings reported by investigators in this field.

2- RESULTS

CAVITY SEALING EFFICIENCY OF SILICATE CEMENT RESTORATIONS.

The radioactive tracer assessment of the cavity sealing efficiency of silicate cement restorations has been shown to depend, amongst other factors, on the type
of radioisotope used. Going, Massler and Dute\textsuperscript{(39)} tested the cavity sealing efficiency of 17 Class V silicate cement restorations placed in extracted human teeth by immersing these specimens in one of three radioisotope solutions ($^{22}$NaCl, $^{45}$CaCl$_2$ and Na$_2$SO$_4^{35}$) for a period of 24 hours. The autoradiographic findings showed a maximum depth of both marginal penetration and dentine penetration by $^{22}$Na for the six specimens immersed in the $^{22}$NaCl solution, a maximum depth of marginal penetration for the four specimens immersed in the Na$_2$SO$_4^{35}$ solution, and the uptake of $^{45}$Ca along (i) the incisal/occlusal cavity wall-restoration interspace, and (ii) the gingival cavity wall-restoration interspace, of each of the seven specimens immersed in the $^{45}$CaCl$_2$ solution (Figure 1).

An analysis of the results presented by Going, Massler and Dute\textsuperscript{(39)} shows that their assessment of the cavity sealing efficiency of amalgam, zinc phosphate cement, zinc oxide-eugenol and acrylic resin restorations (which were tested under the same experimental conditions as the silicate cement restorations using the same radioisotopes as tracers) was less dependent on the type of tracer employed than was their assessment of the cavity sealing efficiency of silicate cement restorations. The depth of micropenetration of amalgam, zinc phosphate cement,
FIGURE 1

RESULTS OF MICROPENETRATION STUDIES
OF GOING, MASSLER AND DUTE (39) (40) *

Histogram showing depth of micropenetration of test restorations by the appropriate radioactive tracers. Depth of penetration scale is explained in Figure 2 (page 27).

*Figure 1, page 276, Going, Massler and Dute (39).
zinc oxide-eugenol and acrylic resin restorations by $^{45}\text{Ca},^{22}\text{Na}$ and $^{35}\text{S}$ was identical and maximal except for the depth of micropenetration of the latter two types of restorations by $^{35}\text{S}$. It was found that $^{35}\text{S}$ had penetrated along the entire tooth-restoration interspace of each zinc oxide-eugenol restoration and of each acrylic resin restoration but had also penetrated into the dentine subjacent to each zinc oxide-eugenol restoration (Figure 1).

Barber and Massler\(^{(3)}\) in 1962, showed that after an immersion period of 24 hours in a $^{45}\text{CaCl}_2$ solution, $^{45}\text{Ca}$ was able to penetrate along (i) the incisal/occlusal cavity wall-restoration interspace, and (ii) the gingival cavity wall-restoration interspace, of each of six Class V unlined silicate cement restorations placed in extracted teeth, whereas under the same experimental conditions, each of six corresponding unlined silicate cement specimens immersed in a $\text{Na}_2^{35}\text{SO}_4$ solution for 24 hours, showed a maximum depth of both marginal penetration and dentine penetration by $^{35}\text{S}$.

Using radiiodine as tracer, Going, Massler and Dute\(^{(40)}\) compared the marginal seal of newly placed silicate cement restorations with that of newly placed silver amalgam, copper amalgam, zinc oxide-eugenol, zinc phosphate cement, red copper cement, temporary
stopping, gold foil and gold inlay restorations. One hundred and sixty one restorations were placed in Class V cavities prepared in extracted human teeth, and then immersed in a Na$^{131}$I solution for 24 hours. The autoradiographic findings for each of the 20 silicate cement specimens showed that $^{131}$I had penetrated the entire tooth-restoration interspace, and in addition had penetrated into the dentine subjacent to the cavity floor. The depth of micropenetration recorded for the silicate cement restorations was comparable to that recorded for silver amalgam, temporary stopping, and zinc oxide-eugenol restorations, and less than that recorded for zinc phosphate cement and acrylic resin restorations, but more than that recorded for gold inlay, gold foil, copper amalgam and red copper cement restorations.

COMPARISON OF DIFFERENT SILICATE CEMENT PREPARATIONS

In 1963, Norman, Swartz and Phillips$^{72}$ studied the cavity sealing properties of six silicate cement preparations [DeTrey's*, Filling Porcelain Improved†, Achatite‡ (with and without glass fibres), Durodent§ and Kryptex† (a silico-phosphate)] using calcium-45 as

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* L.D.Caulk Company, Milford, Delaware.
‡ Vivadent Corporation, Woburn, Massachusetts.
§ Oskar Schaéfer, Jersey City, New Jersey.
tracer, and a radioisotope immersion time of two hours. Restorations were placed in Class V cavities prepared in extracted teeth and stored in tap water for one month prior to testing. The autoradiographic findings were such that the authors found as much variation between the cavity sealing efficiency of individual restorations made from the same material as between the cavity sealing efficiency of restorations made from different materials. These workers applied the same test to restorations made from different types of (i) zinc oxide-eugenol preparations, and (ii) zinc phosphate cement preparations. On the basis of their findings with these materials they reported that the cavity sealing properties of the silicate cement preparations tested were inferior to those of the zinc oxide-eugenol preparations but superior to those of zinc phosphate cement preparations.

Going and Sawinski (43) in 1966 found no difference between the cavity sealing properties of Achadite\textsuperscript{*} silicate cement and S.S. White\textsuperscript{†} silicate cement. Class V cavities were prepared in the opposing surfaces of 20 extracted human teeth, one cavity of each tooth being restored with either Achadite or S.S. White silicate cement and the other cavity restored with

\textsuperscript{*} Establishment Vivadent, Liechtenstein.  
Addent 35* resin. One series of specimens was immersed in a \( \text{CaCl}_2 \) solution for 24 hours, while another series of specimens was subjected to thermal cycling between hot and cold water baths before being immersed in a \( \text{CaCl}_2 \) solution for 24 hours. Both series of silicate cement restorations had a less effective marginal seal than the corresponding Addent 35 restorations. Subjecting silicate cement restorations to thermal cycling did not alter the cavity sealing properties of the material, whereas subjecting Addent 35 restorations to thermal cycling did reduce the cavity sealing properties of the material (Table 2).

EFFECT OF AGING

Nelsen, Wolcott and Paffenbarger\(^{70}\) in 1952 suggested that the interspace between a silicate cement restoration and the adjacent tooth structure may become blocked with corrosion products or other debris as the restoration ages in the oral cavity, thereby limiting the penetration of fluids between the tooth and the restoration. To date, the effect of aging on the ability of radioions to penetrate along the space between silicate cement restorations and the adjacent tooth structure is still open to conjecture, since various

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See footnote * on page 35.
micropenetration studies have shown that the cavity sealing efficiency of silicate cement restorations improves\textsuperscript{(40)}, deteriorates\textsuperscript{(112)} or remains unaltered\textsuperscript{(80)} with aging in vivo, and deteriorates\textsuperscript{(112)} or remains unaltered\textsuperscript{(101)} with aging in vitro. By way of contrast, the effect of aging on the cavity sealing properties of amalgam restorations is well established, the cavity sealing properties of amalgam having been shown to improve as a result of aging either in vivo\textsuperscript{(60)(80)}, or in vitro in either tap water\textsuperscript{(60)(101)}, saliva \textsuperscript{(43)(60)} \textsuperscript{(100)} or sodium sulphide solutions\textsuperscript{(60)}.

Going, Massler and Dute\textsuperscript{(40)} tested the cavity sealing efficiency of 10 old silicate cement restorations using iodine-\textsuperscript{131} as tracer. The only details of the restorations given were that they had been aged in vivo for over 12 months. After extraction, the specimens were immersed in a Na\textsuperscript{131} solution for 24 hours. The autoradiographic findings for the majority of these specimens showed that there was a slight uptake of \textsuperscript{131}I at the tooth-restoration margins. The authors compared these findings with those obtained, under the same experimental conditions, with 20 newly placed Class V silicate cement restorations in situ in extracted human teeth. Each of the restorations placed in vitro showed a maximum depth of marginal penetration and
FIGURE 2

DEPTH OF PENETRATION SCALE USED BY
GOING, MASSLER AND DUTE\(^{(39)(40)}\) AND GOING AND SAWINSKI\(^{(43)}\)

0 = no marginal penetration
1+ = superficial penetration of tracer along tooth-restoration interspace
2+ = penetration of tracer along tooth-restoration interspace to, but not including, the axial cavity wall-restoration interspace
3+ = penetration of tracer along entire tooth-restoration interspace (maximum depth of marginal penetration)
4+ = diffusion of tracer into the dentine subjacent to the restoration
5+ = penetration of tracer into the pulp chamber (maximum depth of marginal penetration and dentine penetration)
some dentine penetration by $^{131}$I. It was concluded from these findings that old silicate cement restorations showed better cavity sealing efficiency than new silicate cement restorations.

Yen(112) restored Class V cavities prepared in vivo in monkey teeth with silicate cement and then allowed the restoration to age in the oral cavity for periods of 2 days and 60 days. In a parallel study, he restored Class V cavities prepared in extracted monkey teeth with silicate cement and then stored the specimens in monkey saliva for periods of 1 hour, 2 days and 60 days. At the end of the respective aging periods, the restorations in situ in the oral cavity were exposed to saliva containing calcium-45 for a period of 4 hours, while the restorations aged in vitro were immersed in monkey saliva containing calcium-45 for 4 hours. Using a topographical sampling method, Yen showed, both in vivo and in vitro, that there was a markedly higher uptake of $^{45}$Ca (i) within the surface layers, and (ii) within the tooth structure adjacent to the restoration walls, of the 60 day restorations than in the same regions of the corresponding newer restorations. Zinc phosphate cement and amalgam restorations tested in vivo and in vitro for cavity sealing efficiency under the same experimental
conditions showed lower amounts of $^{45}$Ca uptake at all time intervals both (i) within the surface layers of the restoration and (ii) in the tooth structure adjacent to the restoration walls. Amalgam restorations showed the lowest values at all time intervals both in vivo and in vitro.

The effect of aging unlined silicate cement restorations up to 6 months in vivo in dog teeth, and up to 3 months in vivo in human teeth was studied by Phillips, Gilmore, Swartz and Schenker\(^{(80)}\). At the end of each aging period, the appropriate teeth were extracted and the restorations and the surrounding tooth structure exposed to a $^{45}$CaCl$_2$ solution for two hours. The authors indicated that the degree of marginal penetration observed with silicate cement restorations was not constant, although over the period of (i) the dog study, and (ii) the human study, they found no appreciable change in the cavity sealing efficiency of this type of restoration. Amalgam, zinc phosphate cement and acrylic resin restorations were also aged in vivo in dog teeth for the same periods of time as the silicate cement restorations. Under these conditions, the cavity sealing efficiency of amalgam and zinc phosphate cement restorations improved with aging, while that of the acrylic resin restorations remained at a constant, and satisfactory, level over
the period of the experiment. The authors compared the cavity sealing efficiency of silicate cement restorations with that of zinc phosphate cement restorations, and reported that, at the end of each aging period, the cavity sealing efficiency of silicate cement restorations was inferior to that of zinc phosphate cement restorations.

In a follow up study to that of Phillips, Gilmore, Swartz and Schenker\(^{(80)}\), Swartz and Phillips\(^{(101)}\) used the same radioisotope tracer technique to assess the cavity sealing efficiency of silicate cement, amalgam, zinc phosphate cement and acrylic resin restorations placed in extracted teeth and stored in tap water for periods up to six months. Except for the cavity sealing efficiency of amalgam, which improved with aging, there was little change overall in the cavity sealing efficiency of the other restorations during the experimental period. Under these experimental conditions, silicate cement restorations showed less marginal penetration than zinc phosphate cement restorations, but a greater uptake of radioisotope within the body of the material than the zinc phosphate cement restorations.

**EFFECT OF CAVITY LININGS**

The application of a cavity varnish to all walls of the cavity prior to the insertion of silicate
Cement has been shown to improve the initial cavity sealing properties of this material \(^{(3)}(102)\).

Swartz and Phillips \(^{(102)}\) compared the initial cavity sealing efficiency of 8 silicate cement restorations placed in Class I and Class V cavities, which had all walls insulated with cavity varnish, with that of 8 silicate cement restorations placed in similar cavities which were unlined. After 2 hours exposure to a \(^{45}\text{CaCl}_2\) solution, the insulated restorations showed less radiosotope uptake along the tooth-restoration interspace than the corresponding unlined restorations. The authors did not give the details of the composition of the cavity varnish used in this experiment.

Barber and Massler \(^{(3)}\) found copal resin varnish effective in improving the initial cavity sealing efficiency of silicate cement restorations. These workers also investigated the effect of (i) a zinc phosphate cement base, (ii) a zinc oxide-eugenol base, and (iii) a calcium hydroxide base on the micropenetration of newly placed silicate cement restorations by two radioactive tracers, calcium-45 and sulphur-35. Restorations were placed in Class V cavities prepared in extracted human teeth and then immersed in one of the two radioisotope solutions for a period of 24 hours.
The autoradiographic findings showed a maximum depth of both marginal penetration and dentine penetration by $^{35}$S for each of the 6 unlined silicate cement restorations immersed in a $\text{Na}_2\text{SO}_4$ solution, and the penetration of $^{45}$Ca along (i) the incisal/occlusal cavity wall-restoration interspace, and (ii) the gingival cavity wall-restoration interspace, of each of the 6 unlined silicate cement restorations immersed in a $^{45}\text{CaCl}_2$ solution. However, restorations lined with a copal resin varnish showed only slight marginal penetration by either tracer, while those lined with a calcium hydroxide base showed maximum marginal penetration by both tracers but no dentine penetration. In contrast, restorations lined with a zinc oxide-eugenol base and restorations lined with a zinc phosphate cement base showed maximum marginal penetration and maximum dentine penetration by both tracers.

**EFFECT OF THERMAL CYCLING**

Going and Sawinski\(^{(43)}\) restored Class V cavities prepared in 20 extracted human teeth with silicate cement. One series of specimens was subjected to thermal cycling by being immersed alternately six times, for 5 minutes each time, in water baths held at 2\(^{\circ}\)C and 68\(^{\circ}\)C. After thermal cycling the specimens were immersed in a
$^{45}$CaCl$_2$ solution for 24 hours. Another series of specimens was not subjected to thermal cycling but was immersed in a $^{45}$CaCl$_2$ solution for 24 hours. It was found that thermal cycling did not alter the cavity sealing properties of the material, since both series of restorations showed a maximum and identical depth of marginal penetration (Table 2).

EFFECT OF CAVITY WALL TEXTURE

Menegale, Swartz and Phillips$^{(64)}$ reported that the texture of the finish of the cavity walls influenced the cavity sealing efficiency of the silicate cement restorations placed therein. Class V cavities were prepared in extracted human teeth and the walls finished in such a way that they were classified as being of either rough, intermediate or smooth texture. After placement, the restorations were stored in tap water for either 48 hours, 30 days or 90 days and then tested for marginal seal by being immersed in a $^{45}$CaCl$_2$ solution for 2 hours. The autoradiographic findings showed that at each time interval, the restorations placed in the rough walled cavities had the least marginal penetration and the restorations placed in smooth walled cavities had the most marginal penetration. A similar trend was observed with amalgam restorations.
placed in cavities with walls of rough, intermediate and smooth texture and aged in tap water for 48 hours, 30 days or 90 days prior to testing, and for gold foil and mat gold restorations placed in cavities with walls of rough and smooth texture and aged 48 hours or 30 days in tap water prior to testing. Acrylic resin restorations evaluated under the same experimental conditions as the silicate cement and amalgam restorations did not show this trend, however, the marginal penetration of acrylic resin restorations was slight at all time intervals.

EFFECT OF RESTORATION FINISHING PROCEDURES

Swartz and Phillips (102) compared the cavity sealing efficiency of 10 silicate cement restorations whose margins were finished immediately after removing the matrix strip with that of 10 similar restorations whose margins were not finished until 20 hours after removing the matrix strip. The restorations finished immediately showed a greater uptake of $^{45}$Ca along the tooth-restoration interspace after a 2 hours immersion in a $^{45}$CaCl$_2$ solution than did the restorations finished after 20 hours. The method used in finishing these restorations was not stated.
CAVITY SEALING EFFICIENCY OF COMPOSITE RESIN RESTORATIONS

Going and Sawinski (43) compared the cavity sealing efficiency of newly placed Addent 35* restorations with that of newly placed Achatite silicate cement, S.S. White silicate cement, Bonfil† acrylic resin, Merdon‡ acrylic resin, Kadon§ acrylic resin, Sevriton§ acrylic resin, gold foil and amalgam restorations. Class V cavities were prepared in the opposing surfaces of extracted human teeth, one cavity in each tooth being restored with Addent 35 and the other cavity with one of the other restorative materials under investigation. All specimens were immersed in a 45CaCl₂ solution for 24 hours. The autoradiographic findings showed that the initial marginal seal of Addent 35 restorations was superior to that of all the silicate cement and acrylic resin restorations and markedly superior to that of amalgam, but inferior to that of gold foil (Table 2). The authors indicated that

* In December, 1966, Addent anterior restorative resin was renamed and marketed as Addent 35, and Addent posterior restorative resin was renamed and marketed as Addent 12 (68). The Addent restorative material used in the studies of Going and Sawinski (43) and Peterson, Phillips and Swartz (77) was Addent 35 (38) (79).

† L.D. Caulk Company, Milford, Delaware
‡ American Consolidated Dental Company, Philadelphia, Pa.
§ C. Ash Inc., Niagara Falls, New York.
### TABLE 2

RESULTS OF MICROPENETRATION STUDY OF GOING AND SAWINSKI *(43)*

<table>
<thead>
<tr>
<th>Restorations studied</th>
<th>Degree of seal penetration (by 45Ca)</th>
<th>Type</th>
<th>No.</th>
<th>Initial</th>
<th>Percolation</th>
<th>2 weeks</th>
<th>4 weeks</th>
<th>8 weeks</th>
</tr>
</thead>
<tbody>
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<tr>
<td><strong>Nonresins</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>a. Silver amalgam</td>
<td></td>
<td>20</td>
<td></td>
<td>5+</td>
<td>Not indicated</td>
<td>Faint 4+</td>
<td>Faint 3+</td>
<td>Faint</td>
</tr>
<tr>
<td>b. Achatite silicate</td>
<td></td>
<td>10</td>
<td></td>
<td>3+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. S.S. white silicate</td>
<td></td>
<td>10</td>
<td></td>
<td>3+</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>d. Gold foil</td>
<td></td>
<td>10</td>
<td></td>
<td>1+, 0</td>
<td></td>
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<tr>
<td><strong>Resins</strong></td>
<td></td>
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<tr>
<td>a. 0, 1+</td>
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<td>b. 0, 2+ IS*</td>
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<tr>
<td>c. 0, 2+ IS</td>
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<td>d. 0, 2+ IS</td>
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<td>e. 0, 1+ IS</td>
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<td>f. 1+, 0</td>
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<td>g. 0, 2+</td>
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<td>h. 0, 1+ IS</td>
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<td></td>
</tr>
<tr>
<td><strong>Addent</strong> (used opposite a, b, c, d above and e, f, g, h below)</td>
<td></td>
<td>135</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>e. Sevrton</td>
<td></td>
<td>33</td>
<td></td>
<td>0, 2+ IS</td>
<td>3+ or 4+</td>
<td>0, 2+ IS</td>
<td>0, 1+</td>
<td>0, 1+</td>
</tr>
<tr>
<td>f. Kadon</td>
<td></td>
<td>26</td>
<td></td>
<td>1+, 2+ IS</td>
<td>3+ or 4+</td>
<td>2+ IS</td>
<td>3+ or 4+</td>
<td>5+</td>
</tr>
<tr>
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<td></td>
<td>7</td>
<td></td>
<td>1+, 2+ IS</td>
<td>3+ or 4+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h. Bonfil</td>
<td></td>
<td>19</td>
<td></td>
<td>1+, 2+ IS</td>
<td>3+ or 4+</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>270</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

*1S= with isolated strips of dentin penetration.

*Page 111, Going and Sawinski (43).*

The depth of penetration scale used in the above table is explained in Figure 2 (page 127). In the above table, where two values are given i.e., 0, 1+, the first value applies to the depth of penetration along the incisal/occlusal cavity wall-restoration interspace, and the second value applies to the depth of penetration along the gingival cavity wall-restoration interspace. Values separated by "or" i.e., 3+ or 4+, indicate that half the specimens had one value and the remaining half the other value.
the presence or absence of Addent Cavity Liner, Bonfil Cavity Primer and Sevriton Cavity Seal under the appropriate restorations made no significant difference to the cavity sealing efficiency of these restorations.

The cavity sealing efficiency of newly placed Addent 35\textsuperscript{*} restorations compared with that of Sevriton, Bonfil and Mer-Don 7\textsuperscript{†} acrylic resin restorations, was studied by Peterson, Phillips and Swartz\textsuperscript{(77)}. Restorations were inserted in Class V cavities prepared in extracted human teeth and then immersed in a $^{45}\text{CaCl}_2$ solution for 2 hours. Addent 35 restorations showed a slight uptake of $^{45}\text{Ca}$ at the tooth-restoration margins. The initial marginal seal of Addent 35 restorations was comparable with that of Sevriton and Bonfil restorations but superior to that of Mer-Don 7 restorations.

**EFFECT OF THERMAL CYCLING**

Going and Sawinski\textsuperscript{(43)} subjected Addent 35 restorations, and Sevriton, Bonfil, Kadon and Merdon acrylic resin restorations to thermal cycling. Achatite silicate cement, S.S. White silicate cement, and gold foil restorations were also subjected to thermal

\* See footnote \* on page 35.

cycling under the same experimental conditions. Cavities were prepared in the opposing surfaces of extracted human teeth, one cavity of each tooth being restored with Addent 35 and the other cavity with one of the other materials under investigation. One series of specimens was immersed alternately, 6 times for 5 minutes each time, in water baths held at 2°C and 68°C, and then immersed in a $^{45}\text{CaCl}_2$ solution for 24 hours, while another series was not subjected to thermal cycling but was immersed in a $^{45}\text{CaCl}_2$ solution for the same period. The depth of micropenetration of Addent, Bonfil, Kadon and Meldon restorations by $^{45}\text{Ca}$ was greater in the restorations subjected to thermal cycling than in the corresponding restorations kept at constant temperature. The increase in micropenetration was proportionately greater in the acrylic resin restorations than in the Addent restorations. In contrast, silicate cement and gold foil restorations showed no increase in micropenetration as a result of thermal cycling (Table 2). Addent Cavity Liner, Bonfil Cavity Primer and Sevriton Cavity Seal were used under the appropriate restorations.

Peterson, Phillips and Swartz$^{(77)}$ restored Class V cavities prepared in extracted human teeth with
Addent 35, Sevriton, Mer-Don 7, and Bonfil. The specimens were cycled over one of two temperature ranges, 15°C - 45°C or 0°C - 60°C, with the appropriate specimens being immersed in each bath for 30 seconds either 10, 50 or 100 times. After thermal cycling, the restorations and surrounding tooth structure were exposed to a $^{45}\text{CaCl}_2$ solution for 2 hours. Restorations subjected to thermal cycling between 15°C and 45°C for 10 cycles showed a depth of micropenetration by $^{45}\text{Ca}$ comparable to that of the corresponding restorations kept at constant temperature, however, restorations subjected to 100 temperature cycles showed a greater depth of micropenetration than the corresponding restorations kept at constant temperature. All restorations subjected to thermal cycling between 0°C and 60°C for either 10, 50 or 100 temperature cycles showed greater marginal penetration by $^{45}\text{Ca}$ than the corresponding restorations kept at constant temperature. The difference in marginal adaptation between the thermally cycled and non-thermally cycled restorations increased in proportion to the number of temperature cycles employed. After thermal cycling, the cavity sealing efficiency of Addent 35 restorations was
reported to be comparable to that of Sevriton and Bonfil restorations but superior to that of Mer-Don 7 restorations.

Wakely and Hoffman(110) subjected restorations made from Addent anterior restorative resin* to thermal cycling while the restorations were immersed in a calcium-45 solution. They found that these restorations, whether they were unlined or lined with Addent Cavity Liner, showed a reduction in cavity sealing efficiency as a result of thermal cycling.

EFFECT OF AGING

Going and Sawinski(43) compared the longer term (up to 8 weeks) cavity sealing efficiency of Addent 35 restorations with that of Sevriton acrylic resin, Kadon acrylic resin and amalgam restorations. Class V cavities were prepared in the opposing surfaces of extracted human teeth, one cavity being restored with Addent 35 and the other with one of the other materials under investigation. Specimens were stored in human saliva at 37°C for periods up to 8 weeks. At the end of each aging period the appropriate specimens were immersed in a $^{45}$CaCl$_2$ solution for 24 hours. The cavity

* See footnote * on page 35.
sealing properties of Addent 35 and Sevriton showed little variation over the period of the experiment, the cavity sealing efficiency of the 8 week restorations being comparable to that of the corresponding newly placed restorations. The cavity sealing properties of Kadon resin deteriorated over the aging period, the 8 week restorations showing a markedly greater depth of micropenetration by $^{45}$Ca than the corresponding newly placed restorations. In contrast, the cavity sealing properties of amalgam improved markedly over the aging period. The newly placed amalgam restorations showed a maximum depth of both marginal penetration and dentine penetration by $^{45}$Ca whereas the corresponding restorations aged 8 weeks showed only a faint uptake of $^{45}$Ca at the tooth-restoration margins (Table 2).

Peterson, Swartz and Phillips (77) compared the initial and longer term cavity sealing efficiency of Addent 35, Sevriton, Bonfil, and Mer-Don 7 restorations by storing these restorations up to 3 months in tap water. The restorations were placed in Class V cavities prepared in extracted human teeth. At the end of each aging period, the appropriate restorations and surrounding tooth structure, were exposed to a $^{45}$CaCl$_2$ solution for
2 hours. The authors stated, "Sevriton restorations demonstrated little or no isotope penetration, even after 3 months storage. Initially, most Bonfil and Addent specimens gave evidence of only a very superficial penetration of isotope at the margins. There did appear to be a slight tendency for this leakage to increase with time. The greatest penetration of the isotope occurred around Mer-Don 7 restorations, and the leakage was considerably greater at 3 months that at 24 hours" (78).

EFFECT OF CAVITY LININGS

The presence of Addent Cavity Liner under Addent restorations has been reported to improve (110), reduce (30), and not effect (43) the cavity sealing efficiency of these restorations.

The autoradiographic findings of Wakely and Hoffman (110) showed that restorations made from either Addent anterior restorative material, or Addent posterior restorative material, and lined with Addent Cavity Liner, had better cavity sealing efficiency than the corresponding unlined Addent restorations. The restorations had been placed in Class V cavities prepared in freshly extracted human teeth, stored in
physiological saline and "refrigerated" for 18 hours and then tested for cavity sealing efficiency by being immersed in a calcium-45 solution for 5 hours. A further series of restorations, made from Addent anterior restorative material, was subjected to thermal cycling while immersed in a calcium-45 solution. Some of the restorations were lined with Addent Cavity Liner and the remainder were left unlined. It was found that thermal cycling reduced the cavity sealing efficiency of both the unlined and lined restorations, and that under these conditions Addent Cavity Liner had little effect in limiting "leakage". *

Dolven and Hampel (30)* restored 28 cavities prepared in monkey teeth with Addent restorative resin. One series of restorations was lined with Addent Cavity Liner, a second series of restorations was left unlined, and a third series of restorations was lined with a copal resin varnish. After an aging period of 3 to 6 weeks

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* The studies of Wakely and Hoffman (110) and Dolven and Hampel (30) were published as abstracts, therefore the amount of experimental detail was necessarily limited. These workers did not indicate whether their assessment of the cavity sealing efficiency of the test restorations was based on the degree of micro-penetration by calcium-45 or only on the degree of marginal penetration by calcium-45. Dolven and Hampel did not state whether the material they used was Addent anterior restorative material or Addent posterior restorative material (see footnote* on page 35).
in vivo, the teeth with restorations in situ were extracted and the cavity sealing efficiency of the restorations tested with $^{45}$Ca. The restorations lined with Addent Cavity Liner had the poorest cavity sealing efficiency, while the unlined restorations and the restorations lined with copal resin varnish had a better, and comparable, degree of cavity sealing efficiency.

The effect of Addent Cavity Liner on the cavity sealing efficiency of Addent 35 restorations was studied by Going and Sawinski$^{(43)}$. Five Class V cavities prepared in extracted human teeth were completely lined with Addent Cavity Liner prior to the insertion of Addent 35, while another four Class V cavities, also prepared in extracted human teeth, were left unlined and restored with Addent 35. The nine restorations were immersed in a $^{45}$CaCl$_2$ solution for 24 hours. The autoradiographic findings showed that there was no marked difference in the cavity sealing efficiency of the unlined and lined restorations.
DEVELOPMENT OF EXPERIMENTAL METHOD

Going, Massler and Dute\(^{(39)}\) in 1960, showed that the radioactive tracer assessment of the cavity sealing efficiency of dental restorations made from the same material could vary with the type of tracer used, and especially so with silicate cement restorations. They had found in preliminary studies that two of the factors that influenced the ability of a radioactive tracer to penetrate along a space between a restoration and the adjacent tooth structure were (i) its ionic charge, and (ii) its chemical activity.

Since the purpose of this study was to investigate the effect of aging, cavity linings and thermal cycling on the micropenetration of composite resin and silicate cement restorations by a radioactive tracer of ionic dimensions, it was necessary to have a tracer with the potential to (i) deeply and selectively penetrate spaces between the test restorations and adjacent tooth structure, and (ii) penetrate the dentine subjacent to the test restorations. Therefore, on the basis of the observations of Going, Massler and Dute\(^{(39)}\), a preliminary study was made of the micropenetration of composite resin and silicate cement restorations by each of five radioactive tracers – \(^{45}\text{Ca as }^{45}\text{CaCl}_2\), \(^{35}\text{S as }\text{Na}_2^{35}\text{SO}_4\),
$^{22}\text{Na}$ as $^{22}\text{NaCl}$, $^{131}\text{I}$ as $\text{Na}^{131}\text{I}$, and $^{14}\text{C}$ as $\text{Na}_2^{14}\text{CO}_3$ (Table 3). These, when dissociated, provided monovalent and divalent cations and anions as tracers.

Freshly extracted canine, premolar, molar and upper central permanent human teeth, without restorations and caries free, apart from some areas of sub-surface decalcification, were used in the preliminary study. After extraction, the teeth were classified according to the patient's age (Group 1 - teeth from patients under 21 years, Group 2 - teeth from patients between 21 and 45 years, Group 3 - teeth from patients over 45 years) and stored in isotonic saline until used. Box type cavities, approximately 2mm deep and 2mm in diameter, were prepared in the intact areas* of the middle third of the facial or lingual surfaces. One cavity was prepared in each tooth following a standardised procedure using both high speed (with water spray) and conventional speed rotary instruments.

Forty five teeth, comprising 15 teeth from each of the three groups, were restored with silicate cement†, and another 45 teeth, comprising 15 teeth from each of the three groups were restored with composite resin‡. The silicate cement and composite resin

* Free from sub-surface decalcification and enamel cracks.
‡ *Addent 35 - 3M Company, St.Paul, Minnesota.*
### TABLE 3
CHARACTERISTICS OF RADIOISOTOPES USED IN PRELIMINARY STUDY

<table>
<thead>
<tr>
<th>Radioisotope *</th>
<th>Energy †</th>
<th>Half-life ‡</th>
<th>Specific Activity of Solution † †</th>
<th>pH of Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beta</td>
<td>Gamma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>⁴⁵Ca (as ⁴⁵CaCl₂)</td>
<td>0.26</td>
<td>Nil</td>
<td>156 days</td>
<td>5.0-6.0</td>
</tr>
<tr>
<td>³⁵S (as Na₂ ³⁵SO₄)</td>
<td>0.167</td>
<td>Nil</td>
<td>87 days</td>
<td>5.0-6.0</td>
</tr>
<tr>
<td>²²Na (as ²²NaCl)</td>
<td>0.54</td>
<td>1.28</td>
<td>2.6 years</td>
<td>5.0-6.0</td>
</tr>
<tr>
<td>¹³¹I (as Na¹³¹I)</td>
<td>0.608</td>
<td>0.364</td>
<td>8.1 days</td>
<td>5.0-6.0</td>
</tr>
<tr>
<td></td>
<td>0.335</td>
<td>0.638</td>
<td></td>
<td></td>
</tr>
<tr>
<td>¹⁴C (as Na₂ ¹⁴CO₃)</td>
<td>0.156</td>
<td>Nil</td>
<td>5,600.0 years</td>
<td>9.0</td>
</tr>
</tbody>
</table>

* Sources of origin: ⁴⁵Ca - Australian Atomic Energy Commission, Lucas Heights, N.S.W. Australia.
  ³⁵S - Atomic Energy Commission of India, Trombay, India.
  ²²Na - Radiochemical Centre, Amersham, Bucks., U.K.
  ¹³¹I - As above
  ¹⁴C - As above

† The Merck Index, 1960(66).

‡ All solutions were adjusted to be iso-osmotic with normal saline by the addition of the necessary quantities of sodium chloride.
were prepared and placed in accordance with the respective manufacturers' directions. After removal of the celluloid matrix strip, the surface of each silicate cement restoration was protected with a coating of low fusing paraffin based wax*, as suggested by Paffenbarger and Stanford (74), and then the specimen was stored in isotonic saline for 24 hours before the margins of the restoration were finished with a sharp scalpel and cuttle fish discs lubricated with Addent Wax†. After the composite resin restorations had polymerised, they were stored in isotonic saline for 24 hours before the margins were finished with sharp burs and cuttle fish discs lubricated with Addent Wax.

To restrict radioactive tracer penetration to the region of the tooth-restoration margins, the roots of the teeth and the enamel surfaces, except for a small area around the tooth-restoration margins, were covered with two layers of varnish‡. During this procedure the surface of each silicate cement restoration was covered

† 3M Company, St. Paul. Minnesota. **Addent Wax** had the advantage of being water soluble and therefore easily removed. As a result, there was less chance of this material blocking the tooth-restoration margins and impeding the penetration of the radioactive tracers than may have occurred with non water soluble lubricating media such as cocoa butter.
‡ Nail polish.
with a layer of Addent Wax to prevent the silicate cement from becoming dehydrated.

The specimens were then stored in isotonic saline for a further 24 hours before they were immersed, crowns downward, in the appropriate radioactive tracer solution. During the immersion period of 24 hours, one series of restorations was kept at 37°C (Series 1), while another series of restorations was subjected to thermal cycling (Series 2). The Series 2 specimens were kept at 37°C in the appropriate radioactive tracer solution for 2 hours, then they were alternately exposed 6 times, for 5 minutes each time, to the same type of radioactive tracer solution held at two different temperatures, 4°C and 60°C. After thermal cycling, the specimens were again exposed to the original tracer solution at 37°C and kept at 37°C for the remainder of the 24 hour immersion period*.

* The thermal cycling temperature range (4°C to 60°C) was the same as that used by Nelsen, Wolcott and Paffenbarger (70) when they tested restorations, placed in vivo, for marginal percolation. They found that 60°C was the upper temperature limit at which hot drinks could be imbibed by test subjects, and they used 4°C as the lower temperature limit for the imbibition of cold liquids. In this study, as in the studies of Brännström and Söremark (17), Swartz and Phillips (101) and Wakely and Hoffman (110), the test restorations were subjected to thermal cycling while exposed to the appropriate radioactive tracer solution. Going and Sawinski (43) and Peterson, Phillips and Swartz (77) used another method whereby the test restorations were first subjected to thermal cycling... (continued on page 50)
At the end of the immersion period, the specimens were removed, washed under running water for one hour and then the layers of varnish were stripped away and the teeth embedded in dental plaster (Plate 3). Two longitudinal plano-parallel cuts were made through the centre of each restoration to produce a tooth-restoration section 600 microns in thickness. After drying, the sections were placed on dental x-ray film* and exposed for a period of 96 hours. At the end of the exposure period, the films and sections were briefly exposed to x-rays following the method described by Going, Massler and Dute(41). The emulsion was then developed according to the manufacturers directions.

The autoradiographs were then examined for evidence of radioactivity (i) along the tooth-restoration

(continued from page 49 )... in hot and cold water baths and then tested for cavity sealing efficiency with a radioactive tracer in solution. The method used in this study gave an indication of the cavity sealing efficiency of the test restorations both during and after thermal cycling, whereas the method used by Going and Sawinski (43) and Peterson, Phillips and Swartz (77) indicated the cavity sealing efficiency of the restorations after thermal cycling.

PLATE 1

 Autoradiographs of ground sections of silicate cement and composite resin restorations (unlined) in situ in extracted human teeth. Prior to the preparation of the sections, the specimens had been immersed in one of five different radioactive tracer solutions ($^{45}$CaCl$_2$, $^{35}$SO$_4$, $^{22}$NaCl, Na$^{131}$I or Na$_2$CO$_3$) for a period of 24 hours. During the immersion period, the specimens had been either kept at a constant temperature (Series 1) or subjected to thermal cycling (Series 2). Magnification x 1.75.
SILICATE CEMENT   COMPOSITE RESIN

\begin{array}{c|c|c|c|c}
45^{\text{Ca}} & \text{Series 1} & \text{Series 2} & \text{Series 1} & \text{Series 2} \\
\hline
35^{\text{S}} & & & & \\
\hline
22^{\text{Na}} & & & & \\
\hline
131^{\text{I}} & & & & \\
\hline
14^{\text{C}} & & & & \\
\end{array}
TABLE 4
ANALYSIS OF AUTORADIOGRAPHIC FINDINGS IN PRELIMINARY STUDY

<table>
<thead>
<tr>
<th>Radioisotope</th>
<th>Restorative Material</th>
<th>Classification of Specimens According to Thermal Treatment</th>
<th>No. of Specimens</th>
<th>No.of Specimens with Maximum Marginal Penetration*</th>
<th>No.of Specimens with Dentine + Penetration and Maximum Marginal Penetration</th>
<th>No.of Specimens with Radioisotope Uptake within Body of Restoration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium-45</td>
<td>Silicate Cement</td>
<td>Series 1 - not thermally cycled</td>
<td>9</td>
<td>9 Nil</td>
<td>Nil</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Series 2 - thermally cycled</td>
<td>9</td>
<td>9 Nil</td>
<td>Nil</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Composite Resin</td>
<td>Series 1 - not thermally cycled</td>
<td>9</td>
<td>9 Nil</td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Series 2 - thermally cycled</td>
<td>9</td>
<td>9 1</td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td>Sulphur-35</td>
<td>Silicate Cement</td>
<td>Series 1 - not thermally cycled</td>
<td>9</td>
<td>9 9</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Series 2 - thermally cycled</td>
<td>9</td>
<td>9 9</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Composite Resin</td>
<td>Series 1 - not thermally cycled</td>
<td>9</td>
<td>9 Nil</td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Series 2 - thermally cycled</td>
<td>9</td>
<td>9 Nil</td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td></td>
<td>Series 1</td>
<td>Series 2</td>
<td></td>
<td>Series 1</td>
<td>Series 2</td>
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<td>---------------------</td>
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<tr>
<td>Silicate Cement</td>
<td>9</td>
<td>See note †</td>
<td>9</td>
<td>See note †</td>
<td>9</td>
<td>See note †</td>
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<tr>
<td>Sodium-22</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite Resin</td>
<td>9</td>
<td>Nil</td>
<td>9</td>
<td>Nil</td>
<td>9</td>
<td>Nil</td>
</tr>
<tr>
<td>Iodine-131</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Silicate Cement</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Composite Resin</td>
<td>9</td>
<td>Nil</td>
<td>Nil</td>
<td>Nil</td>
<td>9</td>
<td>Nil</td>
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<tr>
<td>Carbon-14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicate Cement</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>Nil</td>
</tr>
<tr>
<td>Composite Resin</td>
<td>9</td>
<td>Nil</td>
<td>Nil</td>
<td>Nil</td>
<td>9</td>
<td>Nil</td>
</tr>
</tbody>
</table>

* Penetration of radioisotope along entire tooth-restoration interspace.

† Penetration of radioisotope into dentine underlying the cavity walls. Some specimens showed a very fine strip of dentine penetration emanating from the region of the axio-gingival line angle, however in these instances the presence of this strip was not recorded as dentine penetration.

‡ The path of $^{22}Na$ penetration along the tooth-restoration interspace was impossible to determine due to the poor resolution of the autoradiographic image (Plate 3).
interspace, (ii) in the dentine subjacent to the cavity walls, and (iii) within the body of the restorations.

An analysis of the autoradiographic findings are presented in Table 4 and autoradiographs representative of these findings are shown in Plate 1.

The surface of the composite resin restorations was impervious to each radioactive tracer, however, the surface of the silicate cement restorations was impervious to only one radioactive tracer, carbon-14. Each of the other 4 tracers was able to penetrate the body of silicate cement restorations to some degree.

The cavity sealing efficiency of the Series 1 composite resin restorations was such that none of the restorations immersed in either the $^{45}\text{CaCl}_2$, $\text{Na}_2^{35}\text{SO}_4$, $^{22}\text{NaCl}$, $\text{Na}^{131}\text{I}$ or $\text{Na}_2^{14}\text{CO}_3$ solution showed a maximum degree of marginal penetration by the appropriate tracer. Because of this limited marginal penetration by each of the 5 tracers, it was difficult to detect any marked differences in their penetrating ability. However, the differences in the penetrating ability of these 5 tracers were much more apparent from the autoradiographic findings for the Series 2 composite resin restorations and the Series 1 and Series 2 silicate cement restorations. As a result, the selection of a suitable tracer was based on the
autoradiographic findings for these latter restorations.

Sodium-22 penetrated the entire tooth-restoration interspace of, and into the dentine subjacent to, each of the Series 2 composite resin restorations immersed in the $^{22}\text{NaCl}$ solution. Sodium-22 penetrated into the body of each of the Series 1 and Series 2 silicate cement restorations immersed in the $^{22}\text{NaCl}$ solution, however the diffuse autoradiographic image obscured details of the surrounding tooth structure and made an assessment of the depth of micropenetration impossible.

With the exception of one of the Series 2 composite resin restorations, calcium-45 failed to penetrate the entire tooth-restoration interspace of any of the Series 2 composite resin restorations or any of the Series 1 or Series 2 silicate cement restorations immersed in the $^{45}\text{CaCl}_2$ solution.

Sulphur-35 penetrated the entire tooth-restoration interspace of each of the Series 2 composite resin restorations and each of the Series 1 and Series 2 silicate cement restorations immersed in the $\text{Na}_2\text{SO}_4$ solution. However, sulphur-35 failed to penetrate into the dentine subjacent to any of the Series 2 composite resin restorations, and similarly with two thirds (12 out of 18) of the Series 1 and Series 2 silicate cement restorations, sulphur-35 failed to penetrate the dentine subjacent to the restorations.
Iodine-131 penetrated the entire tooth-restoration interspace of, and into the dentine subjacent to, each of the Series 2 composite resin restorations and each of the Series 1 and Series 2 silicate cement restorations immersed in the Na\textsuperscript{131}I solution.

Carbon-14 penetrated the entire tooth-restoration interspace of, and into the dentine subjacent to, each of the Series 2 composite resin restorations and each of the Series 1 and Series 2 silicate cement restorations immersed in the Na\textsubscript{2}\textsuperscript{14}CO\textsubscript{3} solution.

These findings for the Series 2 composite resin restorations and the Series 1 and Series 2 silicate cement restorations showed that under the conditions of this experiment:

(i) Sodium-22 was an unsatisfactory tracer since the path of sodium-22 penetration of the tooth-silicate cement restoration interspace could not be determined.

(ii) Calcium-45 was also an unsatisfactory tracer since it failed to penetrate the tooth-restoration interspace of the above composite resin and silicate cement restorations as readily as either sulphur-35, iodine-131 or carbon-14.
(iii) Sulphur-35 showed the path of marginal penetration of the above composite resin and silicate cement restorations as readily as iodine-131 and carbon-14, but did not have the same ability as iodine-131 and carbon-14 in penetrating the dentine subjacent to the test restorations.

(iv) Both iodine-131 and carbon-14 readily penetrated the tooth-restoration interspace of, and the dentine subjacent to, the above restorations. However carbon-14 was considered the more satisfactory tracer for two reasons. Firstly, the penetration of carbon-14 was restricted to the areas of the restoration and the surrounding tooth structure that were under investigation, i.e. the space between the restoration and the adjacent tooth structure and the subjacent dentine, whereas iodine-131 not only penetrated these areas but with silicate cement restorations also penetrated into the body of the material. Secondly, the path of carbon-14 penetration was more clearly defined than the path of iodine-131 penetration since the resolution of the autoradiographic images from sections containing carbon-14 was better than those from sections containing iodine-131.
On the basis of these findings, carbon-14 was selected as the most suitable of the 5 tracers for a further investigation of the micropenetration of composite resin and silicate cement restorations.

The results of this study confirm the observations of Going, Massler and Dute\textsuperscript{[39]} that the radioactive tracer assessment of the cavity sealing efficiency of dental restorations made from the same material can vary with the type of tracer used.

The size of the radioactive tracers did not appear to be a major factor influencing their penetrating ability. For example, iodine-131 in solution as $^{131}\text{I}^-$ is more than twice as large as calcium-45 in solution as $^{45}\text{Ca}^{++}$ (Appendix 1), however iodine-131 penetrated the tooth-restoration interspace of the Series 2 composite resin restorations and the Series 1 and Series 2 silicate cement restorations more readily than calcium-45.

Going, Massler and Dute\textsuperscript{[39]} indicated that the ionic charge of a radioactive tracer influenced its ability to penetrate along the space between a restoration and the adjacent cavity walls. The results of this study were such that no definite relationship between the ionic charge of a tracer and its
penetrating ability could be established, although there appeared to be a tendency for the tracers in solution as anions to show the deeper penetration. A comparison of the penetrating ability of sodium-22, in solution as the monovalent cation $^{22}\text{Na}^+$, and iodine-131, in solution as the monovalent anion $^{131}\text{I}^-$, is complicated by the fact that the depth of micropenetration of silicate cement restorations by sodium-22 was impossible to determine, however both sodium-22 and iodine-131 penetrated the tooth-restoration interspace of, and the dentine subjacent to, the Series 2 composite resin restorations. Both carbon-14, in solution as the divalent anion $^{14}\text{CO}_3^-$, and sulphur-35, in solution as the divalent anion $^{35}\text{SO}_4^-$, penetrated the tooth-restoration interspace of the Series 2 composite resin restorations and the Series 1 and Series 2 silicate cement restorations more readily than calcium-45, in solution as the divalent cation $^{45}\text{Ca}^{++}$.

It is possible that the degree of tracer penetration along the space between a restoration and the adjacent cavity walls was influenced by a reaction between the tracer and (i) the restorations, and (ii) the cavity walls. Although the degree of reaction that occurred between calcium-45 and the walls of the silicate cement or composite resin restorations is not
known, it is known that reactions can occur between calcium ions and tooth structure by isoionic exchange with the calcium of the apatite crystals in enamel and dentine (71). If such reactions occurred between calcium-45 and the enamel and dentine of the cavity walls, as well as the loosened layer of tooth substance along the cavity walls (85)(93), it could explain the limited penetrating ability of this tracer. Conversely, the lack of reaction between iodine-131 and the cavity walls (since iodine is not present in tooth structure in detectable amounts, nor is it metabolised by the tooth in any way (6)) may explain the excellent penetrating ability of iodine-131 seen in this study. Any reactions that occurred between carbon-14 and (i) the restorations, and (ii) the enamel and dentine of the cavity walls, were not sufficient, under the conditions of this study, to impede the penetration of this tracer.

The tracers with low energy beta emissions, carbon-14, sulphur-35 and calcium-45 (Table 3) produced autoradiographs with the sharpest detail. This corroborates the observations of Going and Massler (42) who reported that autoradiographs produced by sulphur-35 or calcium-45 showed better resolution than those produced by sodium-22 or iodine-131.
The findings of Going and Sawinski\(^{(43)}\) that thermal cycling had no appreciable effect on the cavity sealing efficiency of silicate cement restorations, and the findings of Going and Sawinski\(^{(43)}\), Peterson, Phillips and Swartz\(^{(77)}\) and Wakely and Hoffman\(^{(110)}\) that thermal cycling reduced the cavity sealing efficiency of composite resin restorations, were confirmed by the results of this study.

None of the radioactive tracers used in this study penetrated into the body of the composite resin restorations, whereas each of these tracers, with the exception of carbon-14, penetrated into the body of the silicate cement restorations. Similar observations on the permeability of silicate cement restorations to radioactive tracers were made by Phillips, Gilmore, Swartz and Schenker\(^{(80)}\) and Swartz and Phillips\(^{(101)}\) who used calcium-45 as tracer, by Going, Massler and Dute\(^{(39)}\) who used calcium-45, sodium-22 and sulphur-35 as tracers, and by Going, Massler and Dute\(^{(40)}\) who used iodine-131 as tracer. The permeability of the body of silicate cement restorations to radioactive tracers suggests there may be additional pathways for penetration into the dentine and pulp with this type of restoration.
The degree of micropenetration of a restoration is a reflection of the permeability of (i) the tooth-restoration interspace, and (ii) the dentine subjacent to the restoration, to the tracers used. Although it has been shown that dentine permeability can vary with the age of a tooth\textsuperscript{(12)}, no attempt was made in this study to relate the degree of micropenetration to the age of the teeth used. However, in order to minimise any bias in the findings due to this factor, an equal number of teeth from each of the three age groups were used for each treatment.

One of the criteria used in the selection of teeth for this study was the absence of enamel defects at the site of cavity preparation. One of the most common defects, in otherwise sound teeth, was enamel cracks. Although cracks can appear in mature enamel for several reasons\textsuperscript{(99)}, it is the author's opinion that many of these are introduced during forceps extraction. For this reason it is advised that special care be taken in extracting teeth to be used in micropenetration studies.
MATERIALS AND METHOD

To study the effect of aging, thermal cycling and cavity linings on the micropenetration of silicate cement and composite resin restorations placed in vivo, it was necessary to have animals from one species, and preferably from a similar age group*, with sufficient numbers of sound contra-lateral teeth suitable for cavity preparation.

Dogs were found to be suitable for this study, for the following reasons:

(i) Dogs of the same breed and similar age were readily available.

(ii) Dogs have adequate numbers of sound contra-lateral teeth of suitable size.

(iii) With dogs, as with other experimental animals, the investigator has control over more of the experimental variables than is possible with human patients.

(iv) The dentine and enamel structure of dog teeth is not markedly different from that of human teeth. Gustafson and Gustafson\(^{(47)}\) have indicated that the enamel of dog teeth has in

* In order to limit, as far as possible, variations in micropenetration (particularly dentine penetration) due to age differences, since dentine permeability has been shown to vary with age\(^{(12)}\).
general a structure similar to that of human enamel, the only difference being in the more regular arrangement of the enamel prisms in dog teeth. Dogs in common with humans have mammalian type dentine (15).

(v) Dogs have been used in previous micropenetration studies by Phillips, Gilmore, Swartz and Schenker (80), Brown (19) and Harris (50).

MATERIALS

ANIMALS

Sixteen greyhound dogs of average weight 25 kilograms and between 2 and 3 years of age were used. The animals were kennelled at The University of Sydney Animal House, before and after the initial operative procedures. Their diet* was designed to provide all the necessary nutrients. Each dog was permanently identified.

RESTORATIVE MATERIALS AND CAVITY LININGS

Silicate cement (S.S. White MQ†) was placed into prepared cavities which were either unlined, or lined

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with one of the following bases:

(i) Zinc phosphate cement (*S.S. White Zinc Cement Improved*).

(ii) Zinc oxide - eugenol cement (*Kalzinol†*).

(iii) Hard setting calcium hydroxide (*Hydrex‡*).

Composite resin (*Addent 35§*) was placed into prepared cavities which were either unlined, or lined with one of the following:

(i) *Addent Cavity Liner§*.

(ii) Hard setting calcium hydroxide base (*Hydrex*).

(iii) *Addent Cavity Liner* placed over a *Hydrex* base**

**RADIOACTIVE TRACER**

Carbon-14, as Na$_2^{14}$CO$_3$, was selected as tracer (see Development of Experimental Method, pages 45 to 61). The Na$_2^{14}$CO$_3$ solution had a specific activity of 200 microcuries per millilitre, a pH of 9.0, and was adjusted to be iso-osmotic with normal saline by the addition of the necessary quantities of sodium chloride.

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† Amalgamated Trade Distributors Ltd., London. W.1.
§ 3M Company, St. Paul. Minnesota.

** Hydrex is one of the few base materials recommended for use with *Addent Cavity Liner*. The manufacturers do not recommend the use of zinc oxide - eugenol, zinc phosphate cement, or calcium hydroxide preparations containing high concentrations of zinc oxide, sodium hydroxide or copper, as bases(67).
METHOD

Restorations were placed in 11 pairs of contralateral teeth in each animal (maxillary 3rd incisor, canine, 3rd premolar, 4th premolar and 1st molar teeth, and mandibular 3rd incisor, canine, 3rd premolar, 4th premolar, 1st molar and 2nd molar teeth). One tooth of each tooth pair was restored at the first operative session, then after a period of either 6 or 12 weeks, at the second and final operative session, the appropriate control restoration was placed in the remaining tooth of each tooth pair*.

PREMEDICATION

Each dog was given a subcutaneous injection of 7.5 mg. morphine sulphate combined with 0.3 mg. atropine sulphate†, one hour preoperatively.

ANESTHESIA

Anaesthesia was obtained by the intravenous injection of thiopentone sodium‡ into the cephalic vein. Usually 12 ml. of thiopentone sodium (0.5 gm. dissolved

* Silicate cement restorations were only placed in the maxillary and lower 2nd molar teeth of each animal, since the facial surfaces of the remaining mandibular teeth were exposed during normal hyperventillation so that any silicate cement restorations placed in the facial surfaces of these teeth could have become dehydrated.

† Drug Houses of Australia Ltd., Sydney.
‡ Intraval Sodium – May and Baker Ltd., Dagenham. U.K.
in 10 ml. of sterile water for injection) was sufficient to keep a 25 kilogram dog anaesthetised for the whole operative procedure*. A 10 inch piece of rubber tubing of 5/8 inch outside diameter was passed via the mouth into the trachea to maintain an airway.

CAVITY PREPARATION

At the initial operative session, box type cavities were prepared in the facial surfaces of the appropriate left maxillary and left mandibular teeth, in the positions shown in Plate 2. The diameter and depth of the cavity preparations varied with the size of the tooth (Table 5). The initial cavity outline was prepared with a No. 17-1 tapering fissure tungsten carbide bur† at 250,000 r.p.m., under a water spray. The final outline, including retention form, was established with a No. 2 inverted cone steel bur‡ at 3,000 r.p.m. and the enamel walls were finished (not bevelled) with a small tapering silicon carbide stone§ at 3,000 r.p.m.

* At this stage a ventriculocordectomy was performed using a method described by Maxwell(63), the only modification being the use of cautery to arrest haemorrhage at the surgical site.

† Meisinger - Hager & Meisinger GmbH., Dusseldorf. Germany
**PLATE 2**

**POSITION OF CAVITY PREPARATIONS IN DOG TEETH**

**MAXILLA**

**MANDIBLE**

I3 = 3rd incisor, C = canine, P3 = 3rd premolar, P4 = 4th premolar, M1 = 1st molar, M2 = 2nd molar.

**TABLE 5**

**SIZE OF CAVITY PREPARATIONS IN DOG TEETH**

<table>
<thead>
<tr>
<th>Tooth</th>
<th>Diameter (approx.)</th>
<th>Depth (approx.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm.</td>
<td>mm.</td>
</tr>
<tr>
<td>Maxilla</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd Incisor</td>
<td>2.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Canine</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>3rd Premolar</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td>4th Premolar</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>1st Molar</td>
<td>2.0</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mandible</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd Incisor</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Canine</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>3rd Premolar</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>4th Premolar</td>
<td>2.0</td>
<td>1.2</td>
</tr>
<tr>
<td>1st Molar</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>2nd Molar</td>
<td>2.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>
At the final operative session, similar cavities were prepared in the same positions in the corresponding right maxillary and right mandibular teeth of each dog. Before the cavity linings or restorations were placed, the cavities were dried with air from a chip syringe. Because of the antisollogogic action of the atropine sulphate used in premedication, no precautions were necessary to maintain a dry field for the operative procedures.

PREPARATION AND PLACEMENT OF CAVITY LININGS

Zinc phosphate cement and zinc oxide-eugenol cement were mixed according to the manufacturers direction to a thick consistency and then placed into the undercut areas. Calcium hydroxide was prepared and placed in accordance with the manufacturers directions. The thickness of each base was kept at approximately one-quarter the depth of the cavity.

Addent Cavity Liner was applied in two coats at 20 second intervals to all cavity walls up to and including the cavo-surface margins. No attempt was made to remove the material from the margins of the cavity.

PREPARATION AND PLACEMENT OF SILICATE CEMENT

Silicate cement was prepared and placed in
accordance with the manufacturers directions. After removal of the celluloid matrix strip, the surface of the restorations was protected with a coating of Addent Wax*.

PREPARATION AND PLACEMENT OF COMPOSITE RESIN

Addent 35 restorations were prepared and placed in accordance with the manufacturers' instructions. The viscosity of the mix made it necessary to force the material into the cavity to ensure the closest possible adaptation with the cavity walls. A tightly rolled pellet of cotton wool held in a pair of tweezers was used to apply the necessary pressure. The cavities were deliberately overfilled and no matrix was used. A protective layer of Addent Wax was flowed over the surface of the material to protect the surface while the material polymerised.

FINISHING OF THE RESTORATION MARGINS

The only finishing done to the margins of silicate cement restorations was carried out 30 minutes after the material had set when any overhanging flash was removed with a sharp scalpel. A protective layer of low fusing paraffin based wax† was then flowed over the surface of

the silicate cement restorations to prevent dehydration of the material while the animal was unconscious and to prevent moisture contamination when the animal recovered and was salivating normally. Each wax coating was removed after 24 hours.

*Addent 35* restorations were finished after the minimum period recommended by the manufacturers (10-12 minutes after the material had polymerised). The extra-coronal bulk of the restorations was reduced with sharp burs and the margins finished with fine sandpaper discs lubricated with *Addent Wax*.

**FINAL OPERATIVE SESSION**

At the final operative session, the surfaces of the silicate cement restorations aged in vivo were coated with paraffin based wax*. Then, after the appropriate control restorations had been placed, the margins finished and the surfaces of the newly placed silicate cement restorations covered with the paraffin based wax, the animals were sacrificed. The complete maxilla and mandible of each dog was removed and immersed in isotonic saline. After approximately 4 hours, the teeth with restorations in situ were

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surgically removed, identified, and then stored in isotonic saline for a further 20-24 hours.

SEALING OF ENAMEL AND ROOT STRUCTURE

To ensure that radioisotope penetration was restricted to the area adjacent to the tooth-restoration margins, all root and enamel surfaces were covered with a varnish leaving a small area of enamel adjacent to the restoration margins uncovered. Once the first layer of varnish had set, a second layer of varnish was applied and allowed to set*

Before the restorations were immersed in the Na$_2^{14}$CO$_3$ solution, the protective layer of wax covering the surfaces of the silicate cement restorations were removed with a sharp scalpel.

IMMERSION IN RADIOACTIVE TRACER SOLUTION

The teeth were placed, crowns downward, in 10 ml. vials which had tight fitting plastic lids. Two or four teeth, depending on the size of the teeth, were placed in each vial and Na$_2^{14}$CO$_3$ solution was introduced into each vial in sufficient quantity for the surface of each restoration to be completely covered.

All restorations from each animal were either (i) immersed in the Na$_2^{14}$CO$_3$ solution and kept at 37°C

* The protective layer of wax was left on the surface of the silicate cement restorations during this period.
for 24 hours (Series 1 restorations), or (ii) immersed in the \( \text{Na}_2^{14}\text{CO}_3 \) solution and subjected to thermal cycling during the 24 hour immersion period (Series 2 restorations).

The Series 2 restorations were kept at 37°C for 2 hours and then alternately exposed 6 times, for 5 minutes each time, to two \( \text{Na}_2^{14}\text{CO}_3 \) solutions at 4°C and 60°C respectively. The thermal cycling procedure was carried out by aspirating the \( \text{Na}_2^{14}\text{CO}_3 \) solution in each vial and replacing it with the same volume of \( \text{Na}_2^{14}\text{CO}_3 \) solution at a temperature of either 4°C or 60°C.

To ensure that the temperature of the tracer solution remained constant over each 5 minute immersion period, the vials were immersed in one of two water baths, the temperatures of which were 4°C and 60°C. After thermal cycling, the \( \text{Na}_2^{14}\text{CO}_3 \) in the vials was replaced with \( \text{Na}_2^{14}\text{CO}_3 \) solution at 37°C, and the temperature of the solution was kept at 37°C for the remainder of the 24 hour immersion period.

After the immersion period, the teeth were removed from the radioactive tracer solution, then washed under running water for one hour before the layers of varnish were stripped away.
TOOTH SECTIONING

The teeth were embedded in dental plaster leaving the surface of the restorations exposed. Each tooth was sectioned longitudinally through the centre of the restoration and through the pulp chamber. Two plano-parallel cuts were made with a 100 mm diameter, diamond edged blade at 1,425 r.p.m. under a continuous water spray to produce a section 600 microns in thickness (Plate 3). If further finishing was required, the sections were polished on 400 grade Wetordry Tri-m-ite Paper.

PREPARATION OF AUTORADIOGRAPHS

The sections were allowed to dry for 2 hours. Under illumination from a Kodak Watten Safelight, Series 6B, the sections were placed directly on dental x-ray film emulsion and clamped between two wooden blocks to ensure close contact between the section and the emulsion (Plate 3). The blocks were placed in light tight boxes for 96 hours, these conditions of exposure having been found the most suitable for the type and concentration of the radioisotope used in this study.

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* Jadem Dembijack Blade No. 27283-E — James Demбитzer, Antwerp, Belgium.
† 3M Company, Sydney.
‡ Eastman Kodak Company, Rochester, New York.
PLATE 3

A

SECTIONING OF SPECIMENS
Photograph shows human teeth embedded in dental plaster prior to sectioning by a diamond edged blade under a continuous water spray. Cuts were made parallel to the lines marked on the teeth.

B

PREPARATION OF AUTORADIOGRAPHS
Photograph shows tooth-restoration sections (human teeth) on bare dental x-ray film before being clamped between the wooden blocks. Each block is lined with a disposable paper napkin.
Before the separation of the film and tooth sections at the end of the 96 hour exposure, the film-tooth assembly inside the light tight boxes was exposed to x-rays for 4 seconds at 60 kvp, 10 ma at a target distance of 4 feet following the method suggested by Going, Massler and Dute\(^{(41)}\). This provided a reference outline of the enamel, dentine, pulp chamber and restoration in relation to radioisotope penetration. The films were then separated from the tooth sections and processed according to the manufacturers directions.

**EVALUATION OF AUTORADIOGRAPHIC FINDINGS**

Each autoradiograph was placed in a photographic slide mount and projected onto a piece of white drawing paper pinned to a vertical board. The distance between the projector and the paper was adjusted so that the autoradiographic image was enlarged exactly 10 times.

(i) **Assessment of marginal penetration.** The outline of the entire tooth-restoration interspace, seen on the projected image of each autoradiograph, was traced onto the white paper, and the depth of marginal penetration by carbon-14 marked on the tracing. The depth of carbon-14 penetration and the length of the entire tooth-restoration interspace were then measured from
the tracing (to the nearest millimetre), and the depth of carbon-14 penetration expressed as a percentage (to the nearest one per cent) of the length of the entire tooth-restoration interspace, i.e. the actual depth of marginal penetration was expressed as a percentage of the maximum potential depth of marginal penetration. The resulting value was termed a Marginal Penetration Value.

(ii) Assessment of dentine penetration. Two outlines were traced, from the projected image, from each autoradiograph which showed dentine penetration (Figure 3):

Outline 1 - An area bounded by (i) the entire axial cavity wall (AB in Figure 3), (ii) the wall of the pulp chamber closest the restoration (CD in Figure 3), (iii) incisal/occlusal border of the dentine penetration emanating from the axio-incisal/occlusal line angle (AC in Figure 3), and (iv) gingival border of the dentine penetration emanating from the axio-
gingival line angle
(BD in Figure 3).

Outline 2 - The area of
carbon-14 uptake within the
area traced in Outline 1.

To measure the proportionate areas of Outline 1 and
Outline 2, the area of paper covered by Outline 1 was cut
out and weighed (to the nearest milligram) and then the
area of paper covered by Outline 2 was cut out and also
weighed. The resulting value for Outline 2 was then

In some autoradiographs showing dentine penetration by
carbon-14, the penetration emanating from the axio-
incisal/occlusal line angle, and/or the axio-gingival
line angle, did not reach the pulp chamber. An
example of the situation where neither the penetration
from the axio-incisal/occlusal line angle nor the
penetration from the axio-gingival line angle reached
the pulp chamber is shown in the diagram below. In
this instance in order to complete Outline 1, the
slope of the line AX was continued to the pulp chamber
and the slope of the line BY was also continued to the
pulp chamber.

![Diagram showing area involved by carbon-14 penetration (Outline 2).]
expressed as a percentage (to the nearest one per cent) of the value for Outline 1, to give a Dentine Penetration Value. The area included in Outline 2 was the cross-sectional area of carbon-14 uptake in the dentinal tubules emanating from the axial cavity wall, while the area included in Outline 1 was regarded as the cross-sectional area that would be involved if the entire length of the dentinal tubules emanating from the axial cavity wall showed an uptake of carbon-14, i.e. a maximum degree of dentine penetration.

Two characteristics of the micropenetration of restorations placed in dog teeth made this method of assessment possible. Firstly, the direction of the dentinal tubules involved in each cavity preparation was such that the major portion of any carbon-14 penetration along the tooth-restoration interspace into the underlying dentine had to pass through the axial cavity wall between the axio-incisal/occlusal line angle and the axio-gingival line angle (Plate 4). Any lateral penetration by carbon-14 into the dentine subjacent to either the incisal/occlusal cavity wall or gingival cavity wall was not included in the assessment of dentine penetration. Secondly, it was found, with few exceptions, that even if dentine penetration was limited to fine strips of penetration by carbon-14, the strips emanated from both the axio-incisal/occlusal line angle and the axio-gingival line angle (although the penetration emanating from the axio-gingival line angle was often more pronounced). In the instances where the penetration did not emanate from both the axio-incisal/occlusal line angle and the axio-gingival line angle, an estimate of the angles BAC or ABD (Figure 3) was made by measuring these angles in other autoradiographs of restorations placed in the same position in the same type of tooth which did show marked dentine penetration. Dentine Penetration Values calculated in these circumstances were only an estimate (see Appendix 3-B).
It was found that using this method of assessing Dentine Penetration Values (DPV) the errors in measurement were homogeneous over the whole range of readings (Appendix 2).

Two assessments of (i) MPV and (ii) DPV were made for each specimen. The final values are an average of these two assessments.

In analysing the results of this study, specimens with a DPV between zero and 20 per cent were considered as having a DPV in the low range, specimens with a DPV between 21 and 80 per cent were considered as having a DPV in the intermediate range, and specimens with a DPV between 81 and 100 per cent were considered as having a DPV in the high range.
PLATE 4

Photomicrographs of ground sections of dog teeth (100 microns in thickness) showing the course of dentinal tubules in the vicinity of cavity preparations. Accompanying each photomicrograph, is an autoradiograph of a ground section of a similar tooth containing an open box type cavity which prior to sectioning had been immersed in a Na₂¹⁴CO₃ solution for one hour (autoradiographs were prepared according to the method described on pages 73-75). The autoradiographs show the direction of carbon-14 penetration from the open cavities into the subjacent dentine.

A  Maxillary third incisor teeth. Photomicrograph, magnification x 6.25; autoradiograph, magnification x 2.5.

B  Mandibular third incisor teeth. Photomicrograph, magnification x 12; autoradiograph, magnification x 2.5.

C  Maxillary canine teeth. Photomicrograph, magnification x 6.25; autoradiograph, magnification x 2.

D  Mandibular canine teeth. Photomicrograph, magnification x 6.25; autoradiograph, magnification x 2.

E  Maxillary 4th premolar teeth. Photomicrograph, magnification x 5; autoradiograph, magnification x 2. (The course of the dentinal tubules shown are similar to those of maxillary 3rd premolar, and mandibular 3rd and 4th premolar teeth. The path of carbon-14 penetration shown is similar to that observed with maxillary 3rd pre- molar, and mandibular 3rd and 4th premolar teeth).

F  Maxillary 1st molar teeth. Photomicrograph, magnification x 6.25; autoradiograph, magnification x 2.5.

G  Mandibular 1st molar teeth. Photomicrograph, magnification x 6.25; autoradiograph, magnification x 2.

H  Mandibular 2nd molar teeth. Photomicrograph, magnification x 6.25; autoradiograph, magnification x 3.
RESULTS

MICROPENETRATION OF COMPOSITE RESIN RESTORATIONS

UNLINED COMPOSITE RESIN RESTORATIONS

Micropenetration data for the 20 pairs of unlined composite resin restorations (24 hour control - 6 week restorations and 24 hour control - 12 week restorations from both Series 1 and Series 2) are shown in Appendix 3-A together with the differences in micropenetration values between each pair of test and control restorations. Marginal Penetration Values (MPV) and Dentine Penetration Values (DPV) are shown separately.

A summary of the MPV and DPV for the 24 hour control, 6 week and 12 week restorations from both Series 1 and Series 2 is shown in Table 6-A, and a summary of the differences in MPV and DPV between paired test and control restorations is shown in Table 6-B.

Examples of the autoradiographic findings for the paired (i) Series 1 twenty four hour control - six week restorations, (ii) Series 1 twenty four hour control - twelve week restorations, (iii) Series 2 twenty four hour control - six week restorations and (iv) Series 2 twenty four hour control - twelve week restorations are shown in Plate 5.
1. EFFECT OF AGING

a. Marginal Penetration Values

A trend towards lower MPV as a result of aging in vivo was observed with the Series 1 unlined composite resin restorations. In the first and second groups of Series 1 twenty four hour restorations, 4 of the 5 restorations and 3 of the 5 restorations respectively, had a maximum MPV, while in the group of Series 1 six week restorations 2 of the 5 restorations had a maximum MPV and in the group of Series 1 twelve week restorations none of the 5 restorations had a maximum MPV. The data in Table 6-B show that with the 5 pairs of Series 1 twenty four hour control - six week restorations, in three instances the 6 week restoration had a lower MPV than the corresponding 24 hour restoration and in two instances the 6 week restoration and the corresponding 24 hour restoration had the same MPV. Furthermore, the 12 week restoration had a lower MPV than the corresponding 24 hour restoration in each of the 5 pairs of Series 1 twenty four hour control - twelve week restorations.

Aging in vivo had no effect on the MPV of unlined composite resin restorations subjected to thermal
TABLE 6

6-A SUMMARY OF MICROPENETRATION VALUES, FROM APPENDIX 3.
FOR UNLINED COMPOSITE RESIN RESTORATIONS

<table>
<thead>
<tr>
<th>Classification of Specimens According to Thermal Treatment</th>
<th>Restoration Aging Period</th>
<th>Marginal Penetration Values</th>
<th>Dentine Penetration Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series 1 - not thermally cycled</td>
<td></td>
<td>No. of Specimens</td>
<td>No. of Specimens with MPV in</td>
</tr>
<tr>
<td>Series 2 - thermally cycled</td>
<td></td>
<td>&lt;100 per cent</td>
<td>Low range (0-20 per cent)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100 per cent</td>
<td>Intermediate (21-80 per cent)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>High Range (81-100 per cent)</td>
</tr>
<tr>
<td>24 hours (1st group)*</td>
<td>5</td>
<td>1</td>
<td>Nil</td>
</tr>
<tr>
<td>24 hours (2nd group)†</td>
<td>5</td>
<td>2</td>
<td>Nil</td>
</tr>
<tr>
<td>6 weeks</td>
<td>5</td>
<td>3</td>
<td>Nil</td>
</tr>
<tr>
<td>12 weeks</td>
<td>5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>24 hours (1st group)*</td>
<td>5</td>
<td>Nil</td>
<td>5</td>
</tr>
<tr>
<td>24 hours (2nd group)†</td>
<td>5</td>
<td>Nil</td>
<td>5</td>
</tr>
<tr>
<td>6 weeks</td>
<td>5</td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td>12 weeks</td>
<td>5</td>
<td>Nil</td>
<td>Nil</td>
</tr>
</tbody>
</table>

* 24 hour restorations from paired 24 hour control - 6 week restorations
† 24 hour restorations from paired 24 hour control - 12 week restorations
### SUMMARY OF DIFFERENCES BETWEEN PAIRED TEST AND CONTROL

**UNLINED COMPOSITE RESIN RESTORATIONS (APPENDIX 3)**

<table>
<thead>
<tr>
<th>Details of Paired Restorations</th>
<th>Marginal Penetration Values</th>
<th>Dentine Penetration Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of Specimens with MPV</td>
<td>No. of Specimens with DPV</td>
</tr>
<tr>
<td></td>
<td>(a) Less than 24 hour control</td>
<td>(a) Less than 24 hour control</td>
</tr>
<tr>
<td></td>
<td>(b) Greater than 24 hour control</td>
<td>(b) Greater than 24 hour control</td>
</tr>
<tr>
<td></td>
<td>(c) Same as 24 hour control</td>
<td>(c) Same as 24 hour control</td>
</tr>
<tr>
<td>Series 1 24 hour control - 6 week</td>
<td>3 Nil 2</td>
<td>5 Nil Nil</td>
</tr>
<tr>
<td>Series 1 24 hour control - 12 week</td>
<td>5 Nil Nil</td>
<td>5 Nil Nil</td>
</tr>
<tr>
<td>Series 2 24 hour control - 6 week</td>
<td>Nil Nil 5</td>
<td>5 Nil Nil</td>
</tr>
<tr>
<td>Series 2 24 hour control - 12 week</td>
<td>Nil Nil 5</td>
<td>5 Nil Nil</td>
</tr>
</tbody>
</table>
PLATE 5

Autoradiographs of ground sections of unlined composite resin restorations in situ in dog teeth. Prior to the preparation of the sections, the specimens had been immersed in a Na\textsubscript{2}^{14}CO\textsubscript{3} solution for 24 hours during which time they had been either kept at a constant temperature (Series 1) or subjected to thermal cycling (Series 2).

A Twenty four hour control restoration and corresponding six week restoration (Series 1) in contra-lateral mandibular canine teeth. (Mag.X 1.75).

B Twenty four hour control restoration and corresponding twelve week restoration (Series 1) in contra-lateral mandibular canine teeth. (Mag.X 1.75).

C Twenty four hour control restoration and corresponding six week restoration (Series 2) in contra-lateral mandibular 1st molar teeth. (Mag.X 2).

D Twenty four hour control restoration and corresponding twelve week restoration (Series 2) in contra-lateral mandibular 4th premolar teeth. (Mag.X 2.5).

Note Any lateral penetration of carbon-14 into the dentine adjacent to the incisal/occlusal cavity wall or into the dentine adjacent to the gingival cavity wall was not included in the assessment of dentine penetration (page 78).
CORRECTION

In Plates 5-12, inclusive, descriptions A and B respectively refer to the A and B autoradiographs from Series 1, and descriptions C and D respectively refer to the A and B autoradiographs from Series 2.
SERIES 1

A

24 HOUR CONTROL

6 WEEKS

B

24 HOUR CONTROL

12 WEEKS

SERIES 2

A

24 HOUR CONTROL

6 WEEKS

B

24 HOUR CONTROL

12 WEEKS
cycling since each of the 24 hour control, 6 week and 12 week Series 2 restorations had a maximum MPV.

Both autoradiographs of the Series 1 twenty four hour control restorations, in Plate 5, show an uptake of carbon-14 along the entire tooth-restoration interspace, while the autoradiograph of the Series 1 six week restoration shows an uptake of carbon-14 along (i) the entire incisal cavity wall-restoration interspace, (ii) the entire gingival cavity wall-restoration interspace, and (iii) almost the entire axial cavity wall-restoration interspace. However, the autoradiograph of the Series 1 twelve week restoration shows an uptake of carbon-14 along (i) the incisal cavity wall-restoration interspace and (ii) the gingival cavity wall-restoration interspace only. The autoradiographs of the Series 2 twenty four hour control, six week and twelve week restorations, each show an uptake of carbon-14 along the entire tooth-restoration interspace.

b. Dentine Penetration Values

A trend towards lower DPV as a result of aging in vivo was observed with both the Series 1 and Series 2 unlined composite resin restorations.

In both groups of Series 1 twenty four hour restorations each of the 5 restorations had a DPV in the
intermediate range, while in the group of Series 1 six week restorations 3 of the 5 restorations had a DPV in the intermediate range and the other 2 restorations had a DPV in the low range. In the group of Series 1 twelve week restorations each of the 5 restorations had a DPV in the low range. With the Series 2 twenty four hour restorations, each of the 5 restorations in the first group had a DPV in the high range, while 4 of the 5 restorations in the second group had a DPV in the high range and the remaining restoration had a DPV in the intermediate range. Each of the 5 Series 2 six week restorations had a DPV in the intermediate range, while 2 of the 5 Series 2 twelve week restorations had a DPV in the low range and the remaining 3 restorations had a DPV in the intermediate range. The data in Table 6-B show that with each of the 5 pairs of (i) 24 hour control - 6 week restorations and (ii) 24 hour control - 12 week restorations, from both Series 1 and Series 2, the 6 week or 12 week restoration had a lower DPV than the corresponding 24 hour control restoration.

The autoradiographs of the Series 1 twenty four hour control restorations (Plate 5) both show an uptake of carbon-14 in the dentine subjacent to the axial cavity wall, while the autoradiograph of the Series 1 six week restoration also shows some carbon-14 uptake
in this region, although less than that shown in the autoradiograph of the corresponding 24 hour restoration. However, the autoradiograph of the Series 1 twelve week restoration shows no carbon-14 uptake in the dentine subjacent to the axial cavity wall. The autoradiographs of the Series 2 twenty four hour control, six week and twelve week restorations each show an uptake of carbon-14 in the dentine subjacent to the axial cavity wall, although the autoradiographs of the 6 week and 12 week restorations both show less carbon-14 uptake in this region than the autoradiographs of their corresponding 24 hour restorations.

2. EFFECT OF THERMAL CYCLING

a. Marginal Penetration Values

A trend towards increased MPV as a result of thermal cycling was observed with unlined composite resin restorations, the trend being more marked with the 6 and 12 week restorations than with the 24 hour control restorations.
The following table, taken from the summary of MPV data in Table 6-A, shows this trend:

<table>
<thead>
<tr>
<th></th>
<th>Number of Specimens with MPV</th>
<th>24 Hour Restorations</th>
<th>6 Week Restorations</th>
<th>12 Week Restorations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(a) &lt;100 per cent (b) 100 per cent</td>
<td>1st group</td>
<td>2nd group</td>
<td>1st group</td>
</tr>
<tr>
<td>Series 1</td>
<td></td>
<td>(a)</td>
<td>(b)</td>
<td>(a)</td>
</tr>
<tr>
<td>Series 2</td>
<td></td>
<td>Nil</td>
<td>5</td>
<td>Nil</td>
</tr>
</tbody>
</table>

In the first and second groups of Series 1 twenty four hour restorations 4 of the 5 restorations and 3 of the 5 restorations respectively, had a maximum MPV, whereas each of the 5 restorations in both the first and second groups of Series 2 twenty four hour restorations had a maximum MPV. A comparison of the MPV of the Series 1 and Series 2 (i) six week restorations and (ii) twelve week restorations shows that, while 2 of the 5 Series 1 six week restorations had a maximum MPV, each of the 5 Series 2 six week restorations had a maximum MPV, and that while none of the 5 Series 1 twelve week restorations had a maximum MPV, each of the 5 Series 2 twelve week restorations had a maximum MPV.

b. Dentine Penetration Values

A trend towards increased DPV as a result of
thermal cycling was observed with unlined composite resin restorations.

The following table, taken from the summary of DPV data in Table 6-A, shows this trend:

<table>
<thead>
<tr>
<th></th>
<th>Number of Specimens with DPV in (a) Low, (b) Intermediate and (c) High Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24 Hour Restorations 1st group</td>
</tr>
<tr>
<td>Series 1</td>
<td>Nil</td>
</tr>
<tr>
<td>Series 2</td>
<td>Nil Nil 5 Nil 5 Nil 1 4</td>
</tr>
</tbody>
</table>

A comparison of the Series 1 and Series 2 restorations shows that:

(i) Each of the 5 restorations in both groups of Series 1 twenty four hour restorations had a DPV in the intermediate range, while each of the 5 restorations and 4 of the 5 restorations, respectively, in the first and second groups of Series 2 twenty four hour restorations, had a DPV in the high range.

(ii) Three of the 5 Series 1 six week restorations had a DPV in the intermediate range and the remaining 2 restorations had a DPV in the low range, while each of the 5 Series 2 six week restorations had a DPV in the intermediate range.
(iii) Each of the 5 Series 1 twelve week restorations had a DPV in the low range, while 3 of the 5 Series 2 twelve week restorations had a DPV in the intermediate range and the remaining 2 restorations had a DPV in the low range.

**COMPOSITE RESIN RESTORATIONS LINED WITH ADDENT CAVITY LINER**

Micropenetration data for the 20 pairs of composite resin restorations lined with Addent Cavity Liner (24 hour control - 6 week restorations and 24 hour control - 12 week restorations from both Series 1 and Series 2) are shown in Appendix 3-A together with the differences in micropenetration values between each pair of test and control restorations. Marginal Penetration Values (MPV) and Dentine Penetration Values (DPV) are shown separately.

A summary of the MPV and DPV for the 24 hour control, 6 week and 12 week restorations from both Series 1 and Series 2 is shown in Table 7-A and a summary of the differences in MPV and DPV between paired test and control restorations is shown in Table 7-B.

Examples of the autoradiographic findings for the paired (i) Series 1 twenty four hour control - six week restorations, (ii) Series 1 twenty four hour control -
twelve week restorations, (iii) Series 2 twenty four hour control - six week restorations and (iv) Series 2 twenty four hour control - twelve week restorations are shown in Plate 6.

1. EFFECT OF AGING

a. Marginal Penetration Values

No general trend in MPV as a result of aging in vivo was observed with either the Series 1 or Series 2 composite resin restorations lined with Addent Cavity Liner.

In both groups of Series 1 twenty four hour restorations 3 of the 5 restorations had a maximum MPV, while in both the group of Series 1 six week restorations and the group of Series 1 twelve week restorations, 4 of the 5 restorations had a maximum MPV. The data in Table 7-B show that with the 5 pairs of Series 1 twenty four hour control - six week restorations, in one instance the 6 week restoration had a lower MPV than the corresponding 24 hour restoration, and in two instances the reverse situation occurred, while in another two instances the 6 week and corresponding 24 hour restoration had the same MPV. Furthermore, with the 5 pairs of Series 1 twenty four hour control - twelve week restorations, in one instance the 12 week
# TABLE 7

## 7-A SUMMARY OF MICROPENETRATION VALUES, FROM APPENDIX 3, FOR COMPOSITE RESIN

**RESTORATIONS LINED WITH ADDENT CAVITY LINER**

<table>
<thead>
<tr>
<th>Classification of Specimens According to Thermal Treatment</th>
<th>Restoration</th>
<th>No.</th>
<th>Marginal Penetration Values</th>
<th>Dentine Penetration Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series 1 - not thermally cycled</td>
<td>Aging Period</td>
<td>Specimens</td>
<td>No. of Specimens with MPV &lt; 100 per cent</td>
<td>No. of Specimens with DPV in Low range Intermediate High range range (0-20 per cent) (21-80 per cent) (81-100 per cent)</td>
</tr>
<tr>
<td>Series 2 - thermally cycled</td>
<td>24 hours (1st group)*</td>
<td>5</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>24 hours (2nd group)†</td>
<td>5</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>6 weeks</td>
<td>5</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>12 weeks</td>
<td>5</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>24 hours (1st group)*</td>
<td>5</td>
<td>Nil</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>24 hours (2nd group)†</td>
<td>5</td>
<td>Nil</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>6 weeks</td>
<td>5</td>
<td>Nil</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>12 weeks</td>
<td>5</td>
<td>Nil</td>
<td>5</td>
</tr>
</tbody>
</table>

* 24 hour restorations from paired 24 hour control - 6 week restorations
† 24 hour restorations from paired 24 hour control - 12 week restorations
### SUMMARY OF DIFFERENCES BETWEEN PAIRED TEST AND CONTROL COMPOSITE RESIN

**RESTORATIONS LINED WITH ADDENT CAVITY LINER (APPENDIX 3)**

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<tr>
<th>Details of Paired Restorations</th>
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<th>Dentine Penetration Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of Specimens with MPV</td>
<td>No. of Specimens with DPV</td>
</tr>
<tr>
<td></td>
<td>(a) Less than 24 hour control</td>
<td>(a) Less than 24 hour control</td>
</tr>
<tr>
<td></td>
<td>(b) Greater than 24 hour control</td>
<td>(b) Greater than 24 hour control</td>
</tr>
<tr>
<td></td>
<td>(c) Same as 24 hour control</td>
<td>(c) Same as 24 hour control</td>
</tr>
<tr>
<td>Series 1 24 hour control - 6 week</td>
<td>(a) 1</td>
<td>(a) 2</td>
</tr>
<tr>
<td>Series 1 24 hour control - 12 week</td>
<td>(b) 2</td>
<td>(b) 2</td>
</tr>
<tr>
<td>Series 2 24 hour control - 6 week</td>
<td>(c) 2</td>
<td>(c) 2</td>
</tr>
<tr>
<td>Series 2 24 hour control - 12 week</td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td></td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td></td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td></td>
<td>Nil</td>
<td>Nil</td>
</tr>
</tbody>
</table>