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Minimal intervention dentistry – a review*

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The concept of minimal intervention dentistry has evolved as a consequence of our increased understanding of the caries process and the development of adhesive restorative materials. It is now recognised that demineralised but noncavitated enamel and dentine can be 'healed', and that the surgical approach to the treatment of a caries lesion along with 'extension for prevention' as proposed by G V Black is no longer tenable. This paper gives an overview of the concepts of minimal intervention dentistry, describes suggested techniques for a minimally invasive operative approach, and reviews clinical studies which have been carried out in this area.

Key words: Dental caries, cavity design, adhesive restorative materials

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For most of the twentieth century the profession has used the cavity classification designed by GV Black[1] whereby caries lesions were treated by a surgical approach requiring the removal of diseased portions of the tooth and extension to areas which were presumed to be caries resistant. The reasons for this included a lack of understanding of the caries process, in particular the potential for remineralisation, and the poor physical properties of available restorative materials. Probably the most serious consequence of the surgical approach was the extent of the cavity which had to be prepared to accommodate the principles of 'extension for prevention'. Since the development of ultra-high speed rotary cutting instruments in the 1950s, there has been a tendency to extend a cavity even further, and the resultant weakening of the tooth crown has led to a marked increase in 'replacement dentistry', wherein there is further loss of tooth structure upon each replacement of a restoration[2].

It is now acknowledged that, in the presence of the fluorine ion, it is possible to remineralise or heal the earliest caries lesion[3], and thus in many cases a surgical approach may be unnecessary, and can be replaced

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by a ‘biological’ or ‘therapeutic’ approach. However, in certain circumstances, a surgical approach is inevitable, and adhesion between the restorative material and both enamel and dentine is an important component for prevention of secondary caries and of pulp damage. Adhesion of resin to enamel became possible in the 1950s[4], adhesion to dentine of polyalkenoic cements in the 1960s[5], and resin-dentine adhesion is now becoming more reliable[6]. When a restoration is required, the use of adhesive restorative materials is preferred because of the potential to prevent bacterial microleakage, as well as the possibility of reinstating some of the physical properties of the tooth crown lost as a result of cavity preparation. It is also possible that demineralised dentine on the cavity floor may be remineralised to some degree; such remineralisation is only possible in the absence of bacterial activity, and is therefore facilitated by an adhesive restorative material.

The profession should now be encouraged to adopt an entirely new attitude to the repair and restoration of demineralised tooth structure. The scientific knowledge is now available to allow major changes to be introduced into the science and art of restorative dentistry. It must be acknowledged and understood that neither fluoride nor the prevention of bacterial microleakage between the tooth and a restoration will, by themselves, be sufficient to prevent further caries activity in any given patient. No restorative material can be regarded as being completely effective in preventing recurrent caries, although the development of materials with a therapeutic potential to stimulate and assist in remineralisation is a possibility. Therefore, all restorative procedures must be carried out only in the presence of well understood preventive techniques, including careful patient education.

In addition, neither can a restorative material be regarded as permanent, and one of the major issues in contemporary restorative dentistry is the diagnosis and management of the ‘failed’ restoration, which is becoming more common due in part to increased life expectancy of the patient and tooth longevity. Traditionally, failed restorations have been totally replaced, but evidence is now accumulating that a repair approach should be adopted in many cases, with the consequent preservation of sound tooth structure[7].

The application of the above concepts has been termed ‘minimal intervention dentistry’, ‘minimally invasive dentistry’ or ‘preservative dentistry’. No formal definition appears to have been proposed for this style of operative dentistry, however, it embodies at least four principles:

- remineralisation of early lesions;
- reduction in cariogenic bacteria, in order to eliminate the risk of further demineralisation and cavitation;
- minimum surgical intervention of cavitated lesions;
- repair rather than replacement of defective restorations;
- disease control.

The purpose of this paper is to discuss the scientific basis and the principles of minimal intervention dentistry, to describe how these principles can be translated into practice, and to discuss evaluations of their clinical applications.

Biological approach to early lesions

At one time, the caries process was thought to be an irreversible sequence of events, beginning with enamel demineralisation followed by protein (collagen) degradation. Thus, the logical treatment was surgical excision of the pathological tissue and replacement with a restorative material. However, it is now recognised that enamel and dentine demineralisation is not a continuous, irreversible process. Rather, there is a demineralisation-remineralisation cycle, in which the tooth structure alternately loses and gains calcium and phosphate ions, depending on the microenvironment. When the pH drops below approximately 5.5, the sub-surface enamel or dentine will begin to demineralise. As the pH rises again, remineralisation may occur[8]. Fluoride plays a critical role in the demineralisation-remineralisation cycle because it enhances uptake of calcium and phosphate ions and can appear in the form of fluorapatite, in which the fluorine ion replaces the hydroxyl ion. Fluorapatite begins to demineralise at a pH of 4.5, rather than 5.5 for hydroxyapatite. Thus, the acid challenge needs to be greater to dissolve fluorapatite than to dissolve hydroxyapatite.

In the early stages of the caries lesion there will be subsurface demineralisation of the enamel. As the lesion progresses into dentine, the surface of the enamel will eventually become cavitated, and it will then be difficult to control plaque accumulation. In areas of difficult access, plaque may hinder the availability of calcium, phosphate and fluoride ions, so remineralisation may be less likely. However, for root caries on an accessible surface, the remineralisation potential is much higher. In any case, remineralisation will be dependent on the maintenance of the collagen matrix of both enamel and dentine, which needs to be present to allow further apatite crystal depositions.

The knowledge of the caries process gained in recent years can be applied as the first principle in ‘minimal intervention dentistry’. Specifically, the traditional ‘surgical’ approach to the early surface lesion (enamel or dentine), can now be superseded by the ‘biological’ or ‘therapeutic’ approach, recognising also that caries is an infectious disease. There are two elements to the biological approach: alteration of the oral environment in order to minimise demineralisation; and application of agents such as chlorhexidine and topical fluoride. A complete discussion of the alteration of the oral environment is beyond the scope of this paper, however, the general modalities which are important are: reduced frequency of refined carbohydrate intake; optimum plaque control; optimum salivary flow; and patient education. Remineralisation of early enamel and dentine lesions is enhanced by the application of topical fluoride, and the various vehicles which are available have been clearly tabulated by McIntyre[9].

The concept of minimal intervention dentistry

The concept of minimal intervention dentistry, sometimes called preservative dentistry, entails a departure from the traditional surgical approach to the elimination of caries lesions which have been identified as radiolucencies in the inner half of the enamel, at the dentino-enamel junction (DEJ), and slightly into dentine, but with little or no evidence of cavitation[10–15]. The delay in treating lesions confined to the inner half of enamel, and even slightly into dentine, is justified on the basis that caries progression through enamel, even in those with active caries, is slow[16,17]. The rate of caries progression in developed countries has been decreasing over recent decades[18], and appears to be even slower in patients who have received regular fluoride treatment or who consume fluoridated water[17,19]. In some populations, it takes 6–8 years for a lesion to progress through enamel[16,20–23], and progress through dentine may also be slow[24–26]. Furthermore, the percentage of radiographically visible approximal lesions in the outer half of dentine that have cavitation in the enamel has declined to approximately 41 per cent[27].

The initial approach must be focused on the management of caries as an infectious disease. In traditional treatment, patients with caries lesions are assumed to be at high risk of both lesion progression and new lesion formation, and restorations are often planned at the first appointment. The most important principles of preservative dentistry are to delay operative intervention for as long as possible[13], to assess whether lesions have resulted in enamel cavitation, and then to assess whether they have progressed through one-third or more of the thickness of dentine. In a broader sense, the focus is on maximum conservation of demineralised, but noncavitated, enamel and dentine. Placement (and replacement) of restorations is avoided until the disease is controlled and operative intervention has become essential because of cavitation, patient discomfort, unacceptable form or function or poor aesthetics. Infection control is applied first, and then caries risk status and evidence of lesion remineralisation can be monitored over extended periods of time.

Preservative dentistry is therefore based on a refined model of care consisting of:

- accurate caries diagnosis;
- classification of the caries severity using radiographs;
- assessment of individual caries risk (high, moderate or low);
- arresting active lesions;
- remineralising and monitoring of cavitated arrested lesions;
- placement of restorations in teeth with cavitated lesions, using minimal cavity designs;
- assessing disease management outcomes (that is, change in various decayed/missing/filled indices) at predetermined time intervals.

The bacterial infection which leads to the production of demineralising acids should be controlled to ensure the arrest of demineralisation and the initiation of remineralisation. To determine if infection control is effective, outcomes must be measured, such as the change in the size of caries lesions. White spot lesions should be described at the initial and at each recall examination, using a periodontal probe to measure the dimensions and location of the geometric centre of the lesion relative to landmark reference points such as cusp tips, fissures, pits, and margins of restorations. A change in lesion size can then be accurately monitored between successive examinations.

In order to assess radiographic changes in approximal radiolucencies, a suitable classification is as follows:

E1 = outer half of enamel
E2 = inner half of enamel
D1 = outer third of dentine
D2 = middle third of dentine
D3 = inner third of dentine.

A tooth or surface with no carious lesion is designated ‘E0’. Dentine is divided into three zones since it enables more conservative criteria to be established, relative to the point at which a decision is made to place a restoration. Traditional dental practice generally adopts the criterion that restorations should be placed when an approximal radiolucency reaches the DEJ, even though only 10 per cent of permanent teeth and 3 per cent of primary teeth show cavitation[27]. Using the preservative dentistry model, restorations are not indicated until the lesion has extended to the D2 region, that is, where the probability of cavitation in the enamel is between 10 per cent and 41 per cent for permanent teeth and between 3 per cent and 28 per cent for primary teeth.

The preservative dentistry model, by focussing on infection control rather than surgical intervention, could result in a 50 per cent reduction in restoration placement[14]. The surgical management of noncavitated, demineralised teeth should be the treatment of last resort, especially for patients who have been shifted from a high or moderate risk status to a low caries risk status.

Adhesive restorative materials

If the caries lesion has reached the stage of cavitation making plaque control difficult or impossible, a surgical approach is generally required. The infected tissue must be removed and replaced with a suitable restorative material, such that form and function are restored and the patient is able to re-establish excellent plaque control. The advent of adhesive restorative materials has enabled minimal intervention principles to be applied to cavity preparation, and the materials which can be used for this purpose are described here.

Glass-ionomer (polyalkenoate) cements[28]

Glass-ionomer cements are available for several purposes, however, there are common properties which apply to all the materials in this class. The two most important properties in the context of minimal intervention dentistry are adhesion to tooth structure and release of fluoride and other ions.

Adhesion arises as a result of an ion exchange between the tooth structure and the cement. The polyalkenoic acid from the glass-ionomer attacks the tooth surface releasing calcium and phosphate ions which subsequently reprecipitate, along with calcium, phosphate and aluminium ions released from the glass, forming a new material which unites the two. There will also be a degree of adhesion between the acid carboxylate groups and dentinal collagen. The strength of the union is dependent upon the tensile strength of the cement itself and any failure will be cohesive within the cement. Thus, the stronger the cement, the higher the measured bond strength[28,29].

The setting reaction of the glass-ionomer cements is an acid-base reaction between the polyalkenoic acid (liquid) and the fluoro-aluminosilicate glass base (powder)[28]. The acid attacks the glass particles, causing a release of calcium, aluminium and fluoride ions. The fluoride ions become incorporated into the matrix, and can readily diffuse into the surrounding tooth structure and into saliva. In addition, set glass-ionomer can take up fluoride from, for example, a fluoride toothpaste. It is commonly assumed that glass-ionomer cements are anticariogenic due to release of fluoride, based on laboratory studies, clinical models and retrospective clinical assessments[30,31]. However, the few prospective clinical trials which assess this property have been equivocal[32]. Glass-ionomer cements have recently undergone further development by the inclusion of a water-soluble polymerisable resin. Although these products are often termed 'light-cured glass-ionomers', this is a poor term and 'resin-modified glass-ionomer' is preferred[33].

The physical properties of the glass-ionomers are important in the context of minimal intervention techniques. Like all water-based cements, they are relatively brittle and, immediately after placement, are not highly wear resistant. Following proper maturation, they have been shown to last well in low stress areas[30,34], and the resin-modified materials can be used for fissure sealing, cervical restorations, approximal anterior lesions in permanent teeth and approximal anterior and posterior lesions in deciduous teeth.

Recent research (Ngo, H; unpublished) suggests that glass-ionomer used to seal an extensive lesion will encourage the remineralisation of demineralised dentine on the floor of the cavity. The effective adhesion will help prevent bacterial microleakage, thus arresting the progress of demineralisation, and the calcium, phosphate and fluoride ions available from the cement will enhance remineralisation. Scientific verification is yet to be established, but clinical observation suggests that it is a valid theory.

Resin composites/dentine bonding agents[35]

Effective bonding of resin composites, particularly to enamel, is a key factor in minimal intervention dentistry. By designing cavities to conserve maximum enamel, retention of the restoration can be effected by enamel bonding, rather than having to remove additional sound tooth structure to achieve macromechanical retention.

Although resin-based dentine bonding agents (DBAs) were first synthesised in the 1950s, substantial laboratory bond strengths were not obtained until Nakabayashi[6] showed that it was possible to 'etch' the dentine, which removes the smear layer and a few micrometres of surface hydroxyapatite, leaving a zone of exposed collagen fibrils. Application of a suitable hydrophilic polymerisable monomer (commonly hydroxyethylmethacrylate; HEMA) will infiltrate the (wet) collagen and establish a mechanical bond; this layer has been variously termed the 'hybrid', 'resin-reinforced' or 'resin-impregnated' layer. The surface of the hybrid layer is rich in methacrylate groups, enabling it to be linked to the methacrylate groups of the matrix of the resin composite. Usually, an intermediate layer of unfilled resin is placed to enhance the wettability of the hybrid layer surface by the filled resin. Clinical success rates are much higher with the hybrid layer-forming DBAs than with their chemical bonding predecessors, but the longevity of this bond in the oral environment remains undetermined. There are also some potential problems with the resin composite itself. In particular, polymerisation shrinkage stress may compromise the marginal integrity, and concern has recently been expressed that such stress may be higher when using high intensity curing lights, compared to the use of lower intensity lights.

Lamination ('sandwich') technique

As noted above, adhesion of glass-ionomer to tooth structure is very effective, but the physical properties of these materials fall short of the universal restorative. At the same time, while the physical properties of resin composites are higher, the adhesion to dentine is still not assured. The combination of the two materials, where resin composite is laminated over glass-ionomer, may offer a useful alternative in situations where the occlusal load is heavy and there is a lack of enamel to provide adhesion to resin composite.

Cavity designs

The developments discussed clearly justify a new approach to the classification of caries lesions. The profession must be encouraged to adopt the biological preservative approach and to abandon the traditional surgical approach. No restorative material can adequately replace enamel and dentine, and their preservation should be paramount in any treatment plan. Prevention and hard tissue preservation are the primary goals. Within this context, the elimination of defects which are likely to accumulate plaque must be considered. Fissure sealing with an adhesive material has been shown to be highly effective[36]. The logical time to seal is shortly after eruption of any tooth which demonstrates a deep,

Table 1 Classification of cavities[41]

Cavity Site	Cavity Size Size 1 Minimal	 Size 2 Moderate	 Size 3 Enlarged	 Size 4 Extensive
Site 1 Pits and fissures	1.1	1.2	1.3	1.4
Site 2 Approximal surfaces	2.1	2.2	2.3	2.4
Site 3 Cervical region	3.1	3.2	3.3	3.4

poorly formed or convoluted fissure system, particularly for patients in a high caries risk group. Ideally the fissure should be sealed prior to the commencement of demineralisation of enamel, although it has been suggested that sealing of an apparently active caries lesion may be sufficient to arrest progress[37]. Conversely, an approximal lesion may not have adequate access, and sealing is generally not an option. As noted above, cavitation of the enamel surface is likely to occur late in the process of demineralisation, but once the surface does break down it will be no longer possible to prevent further plaque accumulation and surgical intervention will be required.

However, regardless of the extent of the cavity, formally prescribed cavity designs should no longer be regarded as mandatory. It is only necessary to gain access to the caries lesion, and remove those areas of enamel and dentine which are infected, degraded and broken down to a point where they are beyond remineralisation[38]. Demineralised enamel surrounding the cavity, and demineralised dentine at the base of the cavity, should be regarded as 'pre-carious', because they can be remineralised and therefore retained[39]. Also, as an adhesive restorative material is to be placed, there will be no need to remove undermined enamel, because it may be able to be supported by the restoration[40]. Both the occlusal load and the wear factor should be taken into account for any particular situation, but as much original tooth structure as possible must be retained.

A more preservative attitude to the restoration of a caries lesion is therefore possible, and the introduction of a new classification should be regarded as an important step in abandoning Black's obsolete system. It is possible to design a classification[41] for caries lesions which is quite different from that of Black, and which will help to guide the profession away from the surgical approach towards the biological approach (*Table 1*).

Preparation for restoration of the minimal occlusal lesion (analogous to the preventive resin restoration[42]) should be as conservative as possible[9]. This lesion generally commences within one section of the fissures on the occlusal surface of a molar. Access is gained using a very fine tapered fissure diamond bur at intermediate high speed under air/water spray (or an enamel hatchet in the Atraumatic Restorative Treatment (ART) technique; see below), and the cavity only opened sufficiently to determine the extent of the caries lesion. A small round bur or an excavator is used to clean the walls, but it is generally not necessary to completely clean the dentine floor because remineralisation is possible, provided that the margin of the restoration is completely sealed from the oral environment[37]. The remaining fissures are explored with the very fine bur only if further sites of demineralised dentine are expected. The subsequent adhesive restoration will then act as both a restoration and a fissure seal.

The approximal posterior lesion may pose problems of access and possibly undermine the marginal ridge. The potential occlusal load must be taken into account, and where possible the margin placed in an area which is not subject to direct occlusion. There are two main options for access, on both posterior and anterior teeth, with a possible third option if the adjacent tooth is being restored at the same time. On a posterior tooth, if the lesion is more than 2.5 mm gingival to the crest of the marginal ridge, it is possible to prepare a so-called 'tunnel' preparation[43,44], by approaching the lesion obliquely through the marginal fossa, and retaining the marginal ridge. If the approximal enamel is cavitated, the periphery is gently cleaned in order to remove friable enamel. No attempt is made to remove any intact but demineralised enamel surrounding the lesion, since it is likely that this can be remineralised. The cavity can then be restored using glass-ionomer, and if necessary laminated occlusally with a resin composite. If the approximal enamel in relation to the lesion is demineralised but not cavitated, it is not necessary to break through the enamel because it is likely that, with good preventive follow up, it can be remineralised. This latter procedure has been termed an 'internal' preparation[45], although other names such as 'partial tunnel', 'blind tunnel' and 'Class I tunnel' have also been used.

If the approximal lesion is close to the marginal ridge, it may be preferable to use a 'slot' or 'minibox' preparation, by entering the carious lesion through the outer slope of the marginal ridge using a very fine tapered fissure diamond bur at intermediate high speed under air/water spray. As much as possible of the marginal ridge is maintained, and the occlusal fissure is not incorporated. The outline is extended to sound enamel, and in most cases there will be a normal contact remaining with the adjacent tooth. The walls are cleaned to allow adhesion to sound dentine and enamel, but there is no need to eliminate all demineralised dentine from the axial wall. Glass-ionomer alone is generally sufficient for restoration, although resin composite may be necessary if the occlusal stress is high. The same principles apply to cavity preparations in anterior teeth, although the 'slot' cavity is generally the preferred approach. Occasionally, in the presence of a strong dominant marginal ridge, it may be possible to employ a tunnel design.

The third alternative for access is only available when a larger Black-style cavity has been prepared in the adjacent tooth, revealing an initial lesion on the approximal surface.

Access will not always be easy, but the situation offers the possibility of a simple and very conservative cavity design which involves neither the occlusal surface nor the marginal ridge. Preparation is straightforward using a tapered diamond bur and a small round bur, possibly with a long shank. A radiopaque adhesive restorative material is essential, in order that the restoration is radiographically visible.

The same basic principles should be applied to the treatment of all other caries lesions. Preservation of natural tooth structure should be the guiding factor for the smallest as well as the largest cavity. The main controlling factor which will need to be taken into account is the occlusal load and thus the wear factor for any given restoration. An apparently simple design may have to be modified under certain circumstances to allow greater strength of the restoration at the expense of some loss of enamel.

'Extension for prevention' is an outmoded concept and adhesive restorative materials can often re-establish support for areas of apparently unsupported enamel. While the adoption of the proposed classification may be inhibited by the apparently profound change which would be brought about, it is evident that the profession has to take this step for the sake of its patients. It is obvious that the traditional surgical approach to the control of caries leads only to a destructive cycle, beginning with excessive tooth reduction for a relatively small lesion, followed by restoration replacement, followed by further cavity modification and eventual tooth loss.

Survival of restorations placed using minimal intervention techniques

As described above, several minimal intervention restoration techniques have been described in the literature, including 'tunnel' and 'internal' restorations, preventive resin restorations, preventive glass-ionomer restorations, posterior approximal 'miniboxes' and 'microchips'[45] and Atraumatic Restorative Treatment (ART)[46] restorations. Unfortunately, there are few publications which assess the clinical efficacy of these techniques. This section reviews the survival of preventive resin and ART restorations for the treatment of single-surface lesions, and tunnel and mini-box restorations for the treatment of minimal approximal lesions.

Table 2 Survival results of preventive resin restorations (PRR) in permanent teeth. N = number at last evaluation.

Source	Duration	N	Survival %
Kilpatrick *et al*., 1996[89]	1.5	66	97
King *et al*.,1996[90]	1.5	532	98
Granath *et al*., 1992[91]	2	87	96
Roth & Conroy 1992[92]	2.3	100	96
Simonsen, 1980[47]	3	232	99
Welbury *et al*., 1990[50]	5	150	95
Houpt *et al*., 1994[51]	9	79	75
Mertz-Fairhurst *et al*., 1998[37]	10	85	87

Preventive resin restorations

The preventive resin restoration (PRR) was first introduced by Simonsen and Stallard in 1977[42,47]. Since then, various PRR techniques have been developed[48,49], most of which have attempted to treat rather small single-surface (mainly occlusal) caries lesions.

The saving in tooth tissue of a PRR approach has been reported. Welbury *et al.*,[50] compared the size of conventional PRR and amalgam cavity preparations, and reported an occlusal surface coverage on average of 5 per cent for PRRs and 25 per cent for amalgam restorations.

The advantages of the PRR for single surfaces, in comparison with conventional methods, include: tooth structure is conserved; the remaining pits and fissures are protected; the risk of microleakage is reduced.

Survival of preventive resin restorations

Several studies, two of which are long-term, have been carried out in order to assess the survival of preventive resin restorations (*Table 2*), and the survival results are based on the need to replace the restoration, that is, a true failure. The long-term survival of PRRs was very high (75 per cent and 87 per cent after 9 and 10 years respectively), and the percentage that survived decreased slowly over time. Secondary caries was the sole reason for failure in the study by Houpt[51], while both caries and marginal breakdown were the reasons observed in the study by Mertz-Fairhurst *et al.*[37]. These investigations not only assessed the survival of PRRs, but also compared the survival of sealed and non-sealed amalgam restorations. After 10 years it was concluded that sealed restorations performed better clinically and exhibited significantly fewer secondary caries lesions.

Atraumatic Restorative Treatment (ART) restorations

The Atraumatic Restorative Treatment (ART) approach evolved in response to the unavailability of restorative care in population groups with limited resources[52], and involves the removal of only soft, demineralised tooth tissue with hand instruments, followed by filling the cleaned cavity and associated pits and fissures with an adhesive restorative material. As conventional high powder:liquid ratio glass-ionomers do not require the use of electricity for mixing and photopolymerisation, their use as the restorative material in the ART technique makes it possible to provide preventive and restorative care in any situation[52]. The resulting restoration may therefore be very similar to Size 1 and Size 2 restorations described above.

However, ART refers to the situation where the dentine lesion is accessible, or can be made so, using hand instruments. This aspect was studied in a low-caries prevalence population[53], and access was achieved in 84 per cent of the diagnosed dentine lesions.

The advantages of ART include:

- only the removal of soft, demineralised dentine and friable enamel is possible, as no rotary instruments are used. This results in minimal cavity preparations which conserve tooth tissue;
- pits and fissures as well as the cavity can be filled or sealed with the restorative material;
- little or no pain is experienced, thereby minimising the need for local anaesthesia;
- anxiety, often found with traditional restorative procedures, is minimised[54];
- only inexpensive and easily available hand instruments are used, and consequently infection control is straightforward and simple;
- the cost is relatively low.

Survival of ART restorations

Since its inception, ART has been subject to evaluation through community field trials, and the results of some of the more important studies are summarised in *Table 3*. Because ART is still relatively new, only three-year survival data are available. However, long-term evaluations using other adhesive restorative materials are in progress.

The short-term results for ART restorations are particularly encouraging, considering that the restorations were placed under less than optimal 'field' conditions. The studies which commenced more recently showed survival rates after three years of between 85 per cent and 88 per cent, and compared favourably with amalgam restorations placed under similar conditions[55]. One clinical trial was carried out in a university setting[56]. Some important points to note from the collective results are:

- the results of early studies[57,58] must be considered as providing 'baseline' data, since the approach was still being developed at the commencement time;
- early studies used glass-ionomers which were not designed specifically for ART. Newer materials designed for ART are now being used, which to some extent accounts for the improved treatment outcomes;
- inexperienced or inadequately trained operators performed less well, which emphasises the need for ART training courses;
- the results pertain only to single-surface restorations in permanent teeth, because these were the predominant cavities in the study populations.

Thus, there is a need for additional research on the survival of ART restorations in primary teeth, the use of ART in multiple-surface cavities and high-risk subjects, and the use of other adhesive restorative materials. In addition, it is essential that ART restorations are evaluated over periods longer than three years.

Table 3 Survival of single-surface ART restorations in the permanent dentition. N = number at last evaluation

Source	Period	Patient age	N	Survival (per cent) 1y	2y	3y
Panthumvanit *et al.*, 1996[58]	1991–94	7–58	144	93	83	71
Mallow *et al.*, 1998[57]	1993–96	12–17	39	78	–	59
Frencken *et al.*, 1998a[46]	1993–96	13–16	197	93	89	85
Frencken *et al.*, 1998b[93]	1994–97	13–16	206	99	94	88
Ho *et al.*, 1999[56]	1995–97	adults	100	98	93	–

Table 4 Survival results of total tunnel restorations in permanent teeth. N = number at last evaluation

Source	Duration (y)	N	Survival %
Svanberg, 1992[60]	3	11	91
Strand *et al.*, 1996[62]	3	161	46
Lumle & Fisher, 1995[59]	5	33	79
Hasselrot, 1997[61]	7	121	39

'Tunnel' and 'internal' restorations

The proposed advantages of the tunnel preparation in comparison with the conventional Class II preparation include the following:

- it is conservative; in particular, the marginal ridge is retained, which contributes to the maintenance of tooth strength;
- the risk for iatrogenic damage to the adjacent approximal surface is minimised or non-existent;
- a normal contact area is maintained;
- the risk of approximal restoration overhangs is reduced.

Survival of 'tunnel' and 'internal' restorations

Only four studies, of relatively short duration, have assessed the survival of tunnel restorations (*Table 4*). In two studies[59,60], only a few restorations were available for evaluation. In the other two studies, failure rates of 9 per cent and 18 per cent per year were reported[61,62]. The reasons for failure included fracture of the marginal ridge, cavitation in approximal enamel (in internal restorations) and secondary caries. Because of the small number of studies available and the small sample size in two of these studies, it is not possible to present a comprehensive summary of the performance of tunnel restorations. However, some important observations are:

- there is a learning curve for tunnel preparations[34,61,63]. Complete removal of infected dentine is demanding, particularly in small tunnel preparations[64,65];
- the risk of failure for internal preparations is higher than that for tunnel restorations[62];
- tunnel restorations had a higher survival rate after three years than slot type conservative Class II amalgam restorations[60]. However, this observation is not entirely in agreement with results reported by Lumley and Fisher[59]. They

reported that there was no difference in survival between tunnel restorations and small Class II amalgam restorations after three years, but after five years the performance of the amalgams was superior;
- equal amounts of tooth substance were sacrificed by tunnel and minimal conventional Class II preparations[64].

Minibox restorations

This preparation was also developed in order to treat caries lesions in approximal surfaces, whilst preserving as much tooth tissue as possible. The marginal ridge is removed, which makes it different from the tunnel preparation, and the literature distinguishes between box-shaped and saucer-shaped preparations; the former has an angled form, while the latter has a rounded form. The cavity is either filled with a resin composite or a glass-ionomer.

Survival of mini-box restorations

Unfortunately, only four studies have been identified (*Table 5*), including one of saucer-shaped glass-ionomer restorations in primary teeth[66] which yielded only nine restorations for three-year evaluation. The longest study reported a survival of saucer-shaped resin composite restorations of 70 per cent after, on average, 7.2 years. Caries and technical deficiencies were the reasons for failures[67]. No failures were observed in box-only resin composite restorations after two years[68] and five years[69].

Table 5 Survival results of mini-box restorations. N = number at last evaluation

Source	Duration	N	Survival %
Kreulen *et al*., 1995[68]	2.2	64	100
Andersson-Wenckert *et al*., 1995[66]	3	9	75
Kreulen *et al*., 1998[69]	5	67	100
Nordbo *et al*., 1998[67]	7.2	36	70

Summary of clinical studies

Relatively few clinical studies of long-term duration are available that have assessed the efficacy of minimal intervention techniques. Preventive resin and mini-box restorations conserve tooth structure and have the potential to survive for a long time, however, this cannot be concluded decisively for tunnel restorations. The little available evidence is inconclusive with respect to the preservation of tooth structure, but points towards insufficient long-term survival of restorations. Despite the ART approach being relatively new, a reasonable number of studies has reported the efficacy of this approach, and because of the use of hand instruments, saving of tooth material is, of necessity, maximal. Future research will determine the long-term survival of ART restorations, and the areas of indication for its use in minimal intervention dentistry.

Repair of defective restorations

Little attention has been given to the repair of defective restorations. Most practitioners choose repair as a treatment option on a case-by-case basis. However, the repair procedure is not well accepted by the profession since it represents a departure from conventional teaching and is considered by many to be 'patchwork dentistry.' Replacement of existing restorations world-wide accounts for between 50 per cent and 71 per cent of each general dental practitioner's activities[70–73]. The replacement of amalgam and resin composite restorations leads to larger restorations which have shorter life spans than their predecessors, and some replacement procedures may cause damage to adjacent teeth. For example, one study of resin composite restorations revealed that the surface area of cavity preparations increased by an average of 75 per cent (approximal aspect) to 71 per cent (occlusal aspect) when clinicians were asked to remove direct and indirect Class II restorations completely using magnifying loupes and their normal technique[74]. There is no question that restoration replacement increases the risk of more complex and more costly subsequent treatment, including root canal therapy.

There have been several studies of repair strengths of 'old' material compared to 'new' material. However, in the individual case, the repair strength may not be an important consideration if it is assessed that the repair does not compromise the strength of the restoration or the retention of the old and new portions.

Amalgam

Hibler *et al.*[75] found that the bond strength of conventional and high-copper dental amalgam repairs was approximately 50 per cent that of non-repaired amalgams, and was unaffected by the type of amalgam alloy used, the time of the repair, or the use of a mercury-rich interface. The latter conclusion contrasts with the earlier finding of Jørgensen and Saito[76], who reported that the bond strength of a conventional amalgam was almost the same as that of the non-repaired amalgam when the surface had been wetted by mercury before the repair. However, the wetting of the original amalgam with mercury is not recommended because of the risks associated with mercury vapour. Berge[77] reported that the flexural strength of repaired specimens was 11 per cent to 51 per cent of the non-repaired controls. The fracture toughness of repaired amalgams was approximately 22 per cent lower than that of the non-repaired specimens.

Resin composite

Swift *et al.*,[78] reported that abrasive blasting of the original resin composite surface, prior to the repair procedure, produced the greatest repair strengths (60 per cent of non-repaired resin composite strength) compared with etching with either hydrofluoric acid or acidulated phosphate fluoride. The strength of repaired resin composites ranges between 25 per cent and 50 per cent of the strength of unrepaired specimens[79]. Although previous reports indicate maximum repair strengths of 78 per cent[80] and 99 per cent[81] for some resin composites, these studies were conducted using specimens that were aged for short times in water.

Repair vs replacement

A correlation between the size of a marginal discrepancy and the presence of secondary caries only exists when the defect is 'very large'[52], however, the traditional rationale has been that marginal breakdown is a precursor of recurrent caries, or is associated with caries already present below the defective margin[82]. The current recommendation is that amalgam replacement is only necessary for very large defects[82]. Because of the wide variability of repaired amalgam and resin composite repair strengths, repairs should be made using cavity designs that ensure independent resistance and retention form for the repair[83,84].

The repair of restorations placed by another clinician must be based on the premise that all carious tissue was removed originally, and that secondary caries has not developed. For a low caries risk patient, the assumption that a caries lesion does not exist beneath defective restorations is reasonable, but for high risk patients the procedure is not as well justified. Since little objective evidence is available for a repair approach over a replacement approach, it is too early to draw definitive conclusions on repair criteria. Repair as a treatment option must be based on the patient's risk for caries, professional judgement of benefits versus risks, and the conservative principles of cavity preparation. Ettinger[85] has published a more complete review of this complex decision-making process.

For a small localised marginal defect, recontouring and repolishing should be the first option considered[86]. In a study of amalgam restorations with small carious and noncarious marginal defects, localised repair with amalgam was found to be highly successful over the two-year observation period[7]. The application of sealant along an entire defective, but non-carious margin, should extend the life span of that restoration and reduce the number of replacement restorations.

For resin composite restorations whose gingival margins are located along root surfaces, good bonding is more difficult to achieve. Thus, repairs in these areas are more critically dependent on the patient's caries risk, since plaque accumulation and leakage at the gingival margin region for a high risk patient is associated with an increased probability of secondary caries. Repair with glass-ionomer cement may be preferable in the cervical area, because of the advantages of reliable adhesion and release of fluoride. Long-term success of the repair may depend on the patient being moved to a low risk status.

In deciding whether to leave or to replace a defective restoration, a decision of 'no treatment' rather than 'replacement' of a restoration is more likely to be correct in a low caries prevalence population. For low-risk patients, the rate of caries progression should be minimal and little or no irreversible change should occur in six months to two years. If the traditional decision is made to replace a restoration independently of the patient's caries risk, the average size of the preparation will increase, the life of the subsequent restoration will decrease, the risk of subsequent endodontic therapy will increase, and there is a 72 per cent probability that caries may be left in the tooth after the preparation is completed[87,88]. Application of the principles of minimum intervention concepts will delay restoration replacement.

However, more clinical research is needed to answer some critical questions regarding decisions to repair or to replace restorations. When evidence of caries is found and removed at a repair site, is the probability of caries at other sites beneath the same restoration sufficiently high to justify the complete removal and replacement of the restoration? For high-risk patients, if a caries lesion exists beneath a restoration with defective margins, will the application of a sealant or dentine bonding agent prevent caries progression and initiation of new lesions? A partial answer to these questions can be derived from the systematic analysis of caries risk factors of individual patients and the reduction of risk by traditional and modern prevention methods. Provided that patients are shifted to a low risk status, repair options will become more justifiable given the absence of supporting scientific data.

With respect to immediate amalgam marginal sealing, only one long-term study has suggested the feasibility of this procedure[37]. In this study, no progression of sealed-in occlusal caries lesions was detected radiographically or using a mirror and explorer at 10 years post-placement. Secondary caries was detected adjacent to the sealant or margin in 12 per cent of teeth with unsealed amalgams, but in only 2 per cent of teeth with sealed amalgams. When carious dentine was not removed, and the teeth were restored with resin composite, only 1 per cent sustained secondary caries at the margins.

Conclusion

In the twenty-first century, greater emphasis must be placed on assessing caries risk, shifting patients to a low caries risk status, remineralising noncavitated lesions, abandoning the surgical approach to caries management and repairing rather than replacing defective restorations. There is a clear need for research to improve the sensitivity of diagnostic methods, to develop site-specific indicators of future caries risk, and to establish clear guidelines on management of caries as an infectious disease.

There is also a major need to analyse the cost-benefit ratio of minimal intervention techniques, so that the effectiveness can be more convincingly demonstrated to the many providers who continue to use the traditional surgical model. However, the public must also be informed of the benefits of these modern methods of diagnosis, prevention, remineralisation, minimal intervention and repair, compared with conventional restorative procedures. Patients' long-term biological and fiscal cost savings will be worth this investment.

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