牙體復形學 **Operative dentistry**

Pulpal Considerations

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學習目標

- 期許同學在瞭解病患的需求及材料的特性後，能依據所學善加利用，做到不僅是幫病患解決病痛的牙醫師，同時也是個讓病患永遠也忘不了的藝術家.

1. 牙齒的生理，解剖形態
2. 齲齒的生理，診斷及治療計劃
3. 窩洞的修形及材料的選擇
4. 窩洞的充填方式及其修飾
5. 美觀性材料的選擇及其運用
6. 變色牙的修飾

參考資料

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Physiologic Considerations

The physiology of the pulp is influenced by several factors that form the basis for the decision to use a sealer, liner, and/or base.

Remaining Dentin Thickness

No material that can be placed in a tooth provides better protection for the pulp than dentin. Dentin has excellent buffering capability to neutralize the effects of cariogenic acids. The remaining dentinal thickness, from the depth of the cavity preparation to the pulp, is the single most important factor in protecting the pulp from insult. In vitro studies have shown that a 0.5-mm thickness of dentin reduces the effect of toxic substances on the pulp by 75%; a 1.0-mm thickness of dentin reduces the effect of toxins by 90%. Little if any pulpal reaction occurs when there is a remaining dentinal thickness of 2 mm or more. Conservation of remaining tooth structure is more important to pulpal health than is replacement of lost tooth structure with a cavity liner or base.

Causes of Pulpal Inflammation

Like other soft tissues, the pulp reacts to an irritant with an inflammatory response. It was previously Believed that pulpal inflammation was the result of toxic effects of dental materials. More recent evidence, however, demonstrates that pulpal inflammatory reactions to dental materials are mild and transitory; significant adverse pulpal responses occur more as the result of pulpal invasion by bacteria or their toxins (Figs 5-1a and 5-1b). Even early enamel caries lesions that extend less than one fourth of the way to the dentinoenamel junction (DEJ) have been shown to induce a pulpal reaction, particularly when the caries lesion has advanced rapidly. This is probably due to an increase in the permeability of enamel, allowing the transmission of stimuli along enamel rods.

Causes of Pulpal Inflammation

As a lesion progresses deeper into the tooth, pulpal reaction increases. When actual pulpal encroachment by bacteria and/or their toxins occurs, severe inflammation or pulpal necrosis frequently occurs. The outward flow of fluid through dentinal tubules does not prevent bacteria or their toxins from reaching the pulp and initiating pulpal inflammation. The caries process also induces the formation of reparative dentin and reactive dentin sclerosis, which increases the protective effects of the remaining dentin.

Causes of Pulpal Inflammation

When bacterial contamination is prevented, favorable responses in pulpal tissue adjacent to many restorative materials have been found. Those materials include amalgam, light-activated resin composite, autocured resin composite, zinc phosphate cement, silicate cement, glass-ionomer cement, and acrylic resin. Acid etching of dentin has long been considered detrimental to the pulp, but the pulp can readily tolerate the effects of low pH if bacterial invasion is prevented.

Causes of Pulpal Inflammation

A number of instrumentation techniques elicit pulpal responses as well. The most common are rotary instruments used in high- and low-speed handpieces for tooth preparation. Tooth preparation can be traumatic to the pulp, and a number of factors affect pulpal reaction. The degree of pulpal reaction is dependent on the amount of friction and desiccation. The key to controlling both is water spray at the site of contact between the bur and tooth structure. This is more important than the amount of water that is used on a rotating bur. Frictional heat generated by tooth preparation can result in burn lesions in the pulp and abscess formation.

Causes of Pulpal Inflammation

While it is often advantageous to refine aspects of a cavity preparation without water spray to aid visibility, this must be done conservatively. The pulp can tolerate dry preparation in a limited area, but the severity of the pulpal reaction increases as the area of dentin subjected to preparation without water spray increases? Another adverse consequence of desiccating dentin in a preparation is that the dentinal fluid is lost from the tubules. The lost fluid may be replaced with chemicals that can elicit a harmful pulpal reaction.

Causes of Pulpal Inflammation

The temperature rise is considerably greater when enamel or a combination of enamel and dentin is prepared versus preparation of dentin alone. Additionally, research has shown that pressure applied during rotary instrumentation has a greater effect on temperature rise than does rotational speed, which is probably why preparation using low-speed rotary instrumentation has been shown to be more traumatic to the pulp than high-speed preparation. Diamonds tend to produce more temperature increase than do carbide burs, and the reaction of the pulp tends to increase as the depth of the cavity preparation increases. Considering these latter two findings, it should not be surprising that an occasional consequence of full-coverage restorations is pulpal necrosis. One study found that 13.3% of teeth with full-coverage crowns required endodontic therapy. Key to controlling temperature rise and minimizing adverse pulpal reaction from rotary instrumentation are adequate air/water spray coolant and light pressure during preparation.

Causes of Pulpal Inflammation

Two new methods for tooth preparation are available--lasers and kinetic cavity preparation, also known as air abrasion. Animal studies have shown that airabrasion cavity preparation is no more traumatic to the pulp than rotary instrumentation)s. Likewise, the use of a variety of lasers, including CO2, Er:YAG, and free electron lasers (FEL) on tooth structure has demonstrated minimal pulpal response, comparable to that of high-speed rotary instrumentation.

Causes of Pulpal Inflammation

One other modality commonly used in conjunction with operative dentistry--electrosurgery to remove gingival tissue for enhanced access during tooth preparation and impression making--may affect the dental pulp. Several animal studies have shown that as long as the contact of the electrosurgery probe is with intact enamel, little or no pulpal reaction ensues. However, if the probe contacts a metallic restoration, adverse and often severe pulpal reaction results. This adverse reaction occurs regardless of whether a cavity base is present or not. The pulpal response is more severe with increased contact time (> 0.4 sec) and decreased dentin thickness between the metallic restoration and the pulp.

Causes of Pulpal Pain

The causes of pulpal pain and sensitivity, while not fully explained, are becoming better understood. Increased intrapulpal pressure on nerve endings, secondary to an inflammatory response, is one mechanism that may explain pain as a result of bacterial invasion. However, this interpretation fails to explain sensitivity that occurs in the absence of inflammation. The explanation for pulpal pain in the absence of inflammation that is most accepted is the hydrodynamic theory. In a vital tooth with exposed dentin, there is a constant slow movement of fluid outward through the dentinal tubules. The hydrodynamic theory proposes that when a stimulus causes the slow fluid movement to become more rapid, nerve endings in the pulp are deformed, a response that is interpreted as pain. Stimuli such as tooth preparation, air drying, and application of cold have been suggested as causes of this sudden, rapid movement of fluid.

Causes of Thermal Sensitivity

Prevention of postoperative thermal sensitivity has long been a rationale for the placement of cavity bases beneath metallic restorations. Initial in vivo research documenting the alleged problem was sparse and poorly controlled. Although one study showed reduced postoperative sensitivity in patients when thick cement bases were used, another demonstrated that, by 6 months postoperatively, few patients had thermal sensitivity regardless of whether a cavity base had been placed. In one survey, 50% of patients questioned 24 hours after restoration placement reported some discomfort, but 78% of these patients described the discomfort as mild and fleeting. Several more recent studies have demonstrated that a significant majority of patients receiving amalgam restorations do not experience postoperative thermal sensitivity, regardless of lesion depth or the absence or presence of a particular cavity sealer or liner. Of those patients with postoperative thermal discomfort, almost all describe it as minor, and it has almost always disappeared within 30 days. Any discussion of the need for protection against postoperative thermal sensitivity must be tempered by the understanding that the prevalence and magnitude of this problem have likely been overestimated.

Theory of Thermal Shock

There are two theories about the cause of thermal sensitivity (usually to cold) following restoration placement, and consequently two philosophies as to how to best address the problem. The first theory states that sensitivity is the result of direct thermal shock to the pulp via temperature changes transferred from the oral cavity through the restorative material, especially when remaining dentin is thin. Protection from this insult would then be provided by an adequate thickness of an insulating material with low thermal diffusivity. It has been noted that resin composite exhibits such low thermal diffusivity that a thermal insulating base would be unnecessary in conjunction with resin composite restorations. Use of an insulating base for thermal protection would, therefore, be limited to metallic restorative materials that exhibit higher rates of temperature transfer.

Theory of Thermal Shock

When a base is used to provide insulation to counter thermal sensitivity in amalgam restorations, the thickness of the material must be minimized in areas subject to occlusal loading. Research has shown that, as the thickness of the base increases, the fracture resistance of the overlying amalgam decreases. Because temperature diffusion through amalgam to the floor of the cavity preparation is effectively reduced by 0.50 to 0.75 mm of basing material, if a base is used, its thickness should be restricted to that dimension. Modulus of elasticity (high modulus of elasticity indicates stiffness; low modulus of elasticity indicates flexibility) is the key property that determines how effectively a base or liner will support an amalgam restoration. As the modulus of elasticity of a basing material decreases, the resistance to fracture of overlying amalgam decreases.

Theory of Pulpal Hydrodynamics

The more widely accepted theory of thermal sensitivity holds that temperature sensitivity is based on pulpal hydrodynamics. Most restorations have a gap between the wall of the preparation and the restorative material that allows the slow outward movement of dentinal fluid (see Fig 5-lb). Cold temperatures cause a sudden contraction of this fluid, resulting in a rapid increase in the flow, which is perceived by the patient as pain. As dentin nears the pulp, tubule density and diameter increase, as does permeability, thus increasing both the volume and flow of pulpal fluid susceptible to the hydrodynamic effects of cold temperatures. This may explain why deeper restorations are sometimes associated with more problems of sensitivity.

Theory of Pulpal Hydrodynamics

According to this theory, if the tubules can be occluded, fluid flow is prevented and a cold temperature does not induce pain. The operative factor in reducing sensitivity to thermal change thus becomes effective sealing of dentinal tubules rather than placement of an insulating material of certain thickness. Scanning electron microscopic observations have revealed significantly higher numbers of open tubule orifices in hypersensitive dentin, lending credence to this theory.

Theory of Pulpal Hydrodynamics

The theory of pulpal hydrodynamics has gained general acceptance in recent years and has changed the direction of restorative procedures away from thermal insulation and toward dentinal sealing. Thus there is increasing emphasis on the integrity of the interface between restorative material and cavity preparation.

Cavity Sealers, Liners, and Bases

The terms varnish, sealer, liner, and base, used to describe a variety of materials, have been a source of confusion in dental literature. In 1995, provided the following definitions for these terms.

Cavity Sealers, Liners, and Bases

1. Cavity sealers: Materials in this category provide a protective coating to the walls of the prepared cavity and a barrier to leakage at the interface of the restorative material and the walls. The term sealer implies total prevention of leakage, but, in fact, the barrier provides various degrees of seal. Sealers usually coat all walls of a cavity preparation. Commonly used sealers fall into two categories:

a. Varnish: A natural rosin or gum (such as copal), or a synthetic resin, dissolved in an organic solvent such as acetone, chloroform, or ether,

b. Resin bonding systems: The adhesive systems designed to provide sealing as well as bonding at the interface between restoration and cavity preparation walls.

Cavity Sealers, Liners, and Bases

2. Cavity liners: Cement or resin coating of minimal thickness (usually less than 0.5 mm) to achieve a physical barrier to bacteria and their products and/or to provide a therapeutic effect, such as an antibacterial or pulpal anodyne effect. Liners are usually applied only to dentin cavity walls that are near the pulp.

Cavity Sealers, Liners, and Bases

3. Cavity bases: Materials to replace missing dentin, used for bulk buildup and/or for blocking out undercuts in preparations for indirect restorations.

Cavity Sealers

Cavity sealers provide a protective coating for freshly cut tooth structure of the prepared cavity. The tooth-restoration interface has always been considered critical in dentistry, a fact apparent in the profession's emphasis on marginal adaptation of dental restorations. The concern is that any interfacial gap, even one not readily apparent under magnification, will allow microleakage. Kidd defined microleakage as the passage of bacteria, fluids, molecules, or ions along the interface of a dental restoration and the wall of the cavity preparation. This process is theorized to cause marginal discoloration, secondary caries, and pulpal pathosis. A summary of some retrospective studies on the causes of clinical failure of existing restorations is provided in Table 5-1.

Cavity Sealers

Clearly, the junction between the restorative material and tooth structure is the source of a considerable number of restoration failures; providing a seamless transition from restoration to tooth structure has long been a goal in dentistry. Cavity sealers, used to fulfill this function, take two forms.

Varnishes

A varnish is a natural gum (such as copal), a rosin, or a synthetic resin dissolved in an organic solvent, such as acetone, chloroform, or ether, that evaporates, leaving behind a protective film. It is used as a barrier against the passage of bacteria and their by-products into dentinal tubules, and it reduces the penetration of oral fluid at the restoration-tooth interface. This film is very thin, usually 2 to 5 μm, and provides no thermal insulation.

Varnishes

Copal varnishes have been used for many years to fill the gap at the amalgam-tooth interface until corrosion products form to reduce it. Varnishes have also been used as barriers against the passage of irritants from cements and bacteria into dentinal tubules. Two applications have been shown to be more effective than a single coat, but a third application does not significantly improve the coating of the cavity walls. Copal varnish is capable of reducing dentin permeability by 69% and significantly reducing microleakage for 4 to 6 months. Varnish is commonly used under amalgam restorations and before cementation of indirect restorations with zinc phosphate cement. Placement of copal varnish before crown cementation with zinc phosphate does not have a detrimental effect on retention.

Adhesive Sealers

The most recent materials to be used as cavity sealers have a demonstrated multisubstrate bonding ability that allows the restorative material to adhere to tooth structure. Examples include adhesive bonding systems, resin luting cements, and glass-ionomer luting cements. The benefits of using adhesive bonding systems to attach resin composite materials to tooth structure are well documented and accepted. It is well established that acid etching will promote a reliable, durable bond to enamel. Its mechanism of action (ie, the diffusion of polymerizable monomers into porosities and channels established in enamel and dentin as a result of the demineralizing action of acid) is well accepted. Bonding systems also provide a chemical bond between the unfilled resin of the adhesive system and the resin composite. Enamel's more consistent and highly mineralized structure provides a more reliable bond than that achieved to dentin.

Adhesive Sealers

Most important, numerous controlled clinical trials have failed to demonstrate a decrease in postoperative sensitivity with the use of adhesive agents under amalgam restorations compared with the use of either traditional sealers and liners or no cavity sealer at all. These results are consistently found regardless of cavity depth and remaining dentin thickness.

Adhesive Sealers

Given these facts, there are some concerns about the use of adhesive resins under amalgam restorations. The insoluble adhesive layer may act as a barrier to prevent amalgam corrosion products from ultimately sealing the tooth-restoration interface. As a result, the dentin bonding resins may potentially put the patient at greater risk in the long term for marginal leakage and recurrent caries. In addition, bonding resins are much more technique sensitive than varnishes, and bonding systems are more expensive and time-consuming. Time and additional research should provide an answer to this dilemma.

Cavity Liners

Cavity liners placed with minimal thickness, usually less than 0.5 mm, provide not only seal, but fluoride release, adhesion to tooth structure, and/or antibacterial action that promotes pulpal health.

Calcium Hydroxide

Calcium hydroxide [$Ca(OH)_2$] has long been used as a liner because of its pulpal compatibility and purported ability to stimulate reparative dentin formation with direct pulpal contact. However, research has shown that not all formulations of $Ca(OH)_2$ have a stimulatory effect on human pulpoblasts. There is a growing belief that reparative dentin formation is assisted, rather than stimulated, and that this is due to the antibacterial action of calcium hydroxide that reduces or eliminates the inflammatory effects of bacteria and their by-products on the pulp.

Calcium Hydroxide

Conventional formulations of calcium hydroxide liners have demonstrated poor physical properties. High solubility of some calcium hydroxide liners may lead to contamination of bonding resins and result in increased marginal leakage. High solubility may also result in softening of the liner and in material loss under poorly sealed restorations. Visible light-activated calcium hydroxide products have overcome most of these deficiencies. They exhibit improved physical properties and significantly reduced solubility. While modulus of elasticity of the light-activated products has been shown to be increased relative to conventional $Ca(OH)_2$ in one study, in another it was lower, with a resulting reduced ability to support an overlying amalgam restoration. These unfavorable physical properties restrict $Ca(OH)_2$ use to application over the smallest area that would suffice to aid in the formation of reparative dentin when a known or suspected pulp exposure exists.

Glass Ionomer

Glass ionomer has been used as a cavity liner in an attempt to take advantage of two highly desirable properties: chemical bond to tooth structure and fluoride release. Although fluoride release from glass ionomer decreases with time, sustained release has been demonstrated with corresponding uptake into adjacent tooth structure. This is thought to aid in anticariogenic activity. Like zinc phosphate, glass ionomer is quite acidic on initial mixing but tends to neutralize within 24 hours. Pulpal response to both visible light-activated and conventional glass-ionomer formulations has been shown to be favorable, probably because glass ionomer decreases interfacial bacterial penetration. The exact mechanism by which this is achieved is uncertain, but it may be due to one or more of the following: fluoride release, initial low pH, chemical bond to tooth structure (physically excluding bacteria) or release of a metal cation.

Glass Ionomer

Both visible light-activated and conventional glass-ionomer liners exhibit good physical properties, with the conventional version exhibiting reduced interfacial gap formation, a higher modulus of elasticity, and subsequently improved support for amalgam restorations. Glass ionomer has been shown to reduce microleakage under amalgam restorations. Conventional glass ionomers are relatively soluble in an acidic environment and are susceptible to rapid surface deterioration when subjected to acid etching. Visible light-activated glass ionomers show improved resistance to acid solubility while maintaining fluoride release and bond to tooth structure. Therefore, the visible light-activated formulations are more desirable for use with resin composite restorations.

Glass Ionomer

Glass-ionomer cements (GIC) have been recommended as liners under resin composite restorations to reduce microleakage. The use of GIC as an intermediate layer between dentin and resin composite, particularly in Class 5 restorations, is often referred to as the "sandwich technique." Glass ionomer use, most often in conjunction with Class 2 resin composite restorations, is sometimes called the "bonded-base" technique. Either the sandwich or bonded-base techniques can be "open," in which the GIC at the gingival margin is exposed, or "closed," in which the GIC is completely covered by resin composite. Glass-ionomer liners, both visible light-cured and autocured, have been studied extensively for their ability to seal the interface between resin composite and the cavity preparation. The preponderance of in vitro evidence indicates that GIC liners perform at least as well as, and in most cases significantly better than, bonding resins used alone to seal the restoration-tooth interface. This is probably due to the delayed set and increased strain capacity provided by the GIC. In addition, the open sandwich or bonded-base restoration appears to be superior to the closed technique in achieving this superior seal.

Cavity Bases

As previously stated, cavity bases are used as dentin replacement materials, allowing for less bulk of restorative material or blocking out undercuts for indirect restoration (Figs 5-2a and 5-2b). Although cavity bases generally are not used for pulpal protection or health, they are briefly described here. Zinc Oxide-Eugenol and Zinc Phosphate Cements. Zinc oxide-eugenol and zinc phosphate cements have been used for a number of years as bases for a variety of restorative materials. Although both provide excellent thermal insulation, and zinc phosphate cement exhibits superior physical properties, their use has diminished in recent years with the growing question of their benefit to pulpal health and with the advent of materials that are adhesive to dentin and release fluoride.

Glass Ionomer

As previously mentioned, glass-ionomer materials have excellent physical properties, with the conventional versions offering excellent modulus of elasticity and restoration support. As a result, glass ionomers can be used as cavity bases as well as cavity liners.

Guidelines for Basing, Lining, and Sealing

Clinicians must always consider the limitations of currently available materials. The best possible base for any restoration is sound tooth structure. The following are guidelines for placement of bases, liners, and sealers:

Guidelines for Basing, Lining, and Sealing

1. Do not remove sound tooth structure to provide space for a base. Maintaining sound dentin will enhance restoration support and provide maximum dentin thickness for pulpal protection.

Guidelines for Basing, Lining, and Sealing

2. Use bases as indicated for build-up materials and block-out materials for cemented indirect restorations. If used for direct amalgam restorations or bonded restorations, minimize the extent of the base. Basing a preparation to "ideal" depth and internal form is contraindicated. Bases in cavity preparations for amalgam restorations and bonded resin or ceramic restorations lead to decreased bulk of restorative material and increased potential for restoration fracture.

Guidelines for Basing, Lining, and Sealing

3. Use the minimum thickness of liner necessary to achieve the desired result. For liners under amalgam restorations, this should not exceed 0.5 mm.

Guidelines for Basing, Lining, and Sealing

4. Currently, there is no convincing evidence for the routine use of adhesive sealers (dentin bonding resins) under metallic restorations.

Direct and Indirect Pulp Capping

Pulp capping is defined as "endodontic treatment designed to maintain the vitality of the endodontium." Several favorable conditions must be present before considering direct or indirect pulp capping:

Direct and Indirect Pulp Capping

1. The tooth must be vital and have no history of spontaneous pain.
2. Pain elicited during pulp testing with a hot or cold stimulus should not linger (persistent) after stimulus removal.
3. A periapical radiograph should show no evidence of a periradicular lesion of endodontic origin.
4. Bacteria must be excluded from the site by the permanent restoration.

Direct and Indirect Pulp Capping

If these conditions can be met, an indirect pulp capping procedure is much preferable to a direct pulp capping procedure. Because of the uncertainty for success with either procedure, pulpal health should be monitored for several months in teeth that are to receive castings or serve as abutments for fixed or removable partial dentures. If the pulpal status of a tooth is uncertain, the clinician should consider endodontic therapy before initiating restorative treatment.

Direct Pulp Capping

Animal studies have demonstrated that direct pulpal exposures can heal normally, but a bacteria-free environment is required. The adverse consequences of bacterial contamination of the pulp have been well documented. Therefore, the only reasonable chance that a direct pulp cap has to permit formation of a dentin bridge and to maintain pulp vitality is under the most ideal conditions. If a large number of bacteria from a caries lesion or exposure to the oral flora have contaminated the pulp, the likelihood of regaining or maintaining a healthy pulp is slight. In addition, aged pulps have increased fibrosis and a decreased blood supply, and thus a decreased ability to mount an effective response to invading microorganisms.

Direct Pulp Capping

In one clinical study of direct pulp capping of 38 patients over 3 years, no relationship between success and factors such as patient age, tooth type, or size of exposure was found. However, in a larger study of both direct and indirect pulp capping involving 592 patients over a 24-year period, age, tooth type, and extent of exposure did have a bearing on success. The degree of bleeding affects the success of direct pulp capping; increased bleeding is associated with increased likelihood of failure.

Direct Pulp Capping

Direct pulp capping should be attempted only when a small mechanical exposure of an otherwise healthy pulp occurs. The tooth must be isolated with a rubber dam, and adequate hemostasis must be achieved. The exposure should be covered with calcium hydroxide because of its documented ability to provide the highest percentage of success (Fig 5-3). It must be possible to restore the tooth with a well-sealed restoration that will prevent subsequent bacterial contamination.

Indirect Pulp Capping

An indirect pulp capping procedure (Fig 5-4) should be considered when there is a radiographically evident, deep carious lesion encroaching on the pulp and the tooth has no history of spontaneous pain and responds normally to vitality tests. Pulp exposure must be avoided; if it occurs, it should be regarded as an iatrogenic event. A direct pulp capping procedure should be necessary only if the operator inadvertently exposes the pulp in attempting an indirect pulp capping procedure. With a deep carious lesion, the indirect pulp capping procedure is always preferred to a direct pulp capping procedure.

Indirect Pulp Capping

In the procedure (Figs 5-5 and 5-6), after the initial entry into the carious dentin (Fig 5-5c), a spoon excavator or large round bur, rotating very slowly in a low-speed handpiece, should be used to excavate the caries-softened dentin (Fig 5-6e). Demineralized dentin not near the pulp should be completely removed, leaving hard, sound dentin. As the caries excavation nears the pulp, caution must be exercised to avoid pulpal exposure. If a bur has been used to excavate softened dentin, a spoon excavator may be used to aid in tactile detection of softened dentin. The wet (soft, amorphous) carious dentin should be removed; as the pulp is approached, the dry, fibrous, demineralized dentin that gives some moderate resistance to gentle scraping with a spoon excavator should be allowed to remain.

Indirect Pulp Capping

Caries-disclosing dyes may be used to assist in caries excavation (Figs 5-5e to 5-5g and 5-6b to 5-6f). Studies have demonstrated the benefit of these dyes to aid in identification and removal of demineralized dentin, and to greatly reduce remaining viable bacteria. It must be recognized that the dyes stain not only demineralized dentin, but anything porous, such as debris that may have been left in the cavity preparation. In addition, noncarious deep dentin will absorb the dye, because of the increased number and size of dentinal tubules in deep dentin; if this dye-stained sound dentin is removed, pulp exposure will result. If the operator uses a caries-disclosing dye, he or she must be aware of this characteristic of dye use in deep dentin. Any residual dye left on dentin before use of a dentin bonding system will cause a significant reduction in bond strength. This dye-stained dentin should be covered with a liner before placement of a bonding resin.

Calcium Hydroxide vs Dentin Bonding Agents

It has been suggested that dentin bonding agents may be used for direct and indirect pulp capping. The rationale is based on the belief that an effective, permanent seal against bacterial invasion is provided and will promote pulpal healing. This theory is supported by a number of studies. Animal research has shown good compatibility of mechanically exposed pulps to visible light-activated resin composites when bacteria are excluded. In addition, adhesive resins and pulpal tissues were shown to be compatible for up to 90 days when the smear layer was removed from cavity walls before the application of a dentin adhesive, confirming the ability of the bonding agents to minimize bacterial invasion for this period of time. Several animal studies have shown that while calcium hydroxide may result in faster dentin bridge formation, adhesives can be successfully associated with dentin bridge formation, and this can occur without long- term pulpal inflammation. Many components of dentin bonding agents are directly toxic to pulp cells, but their release is rapid and slows dramatically with time, so these materials are not thought to be deterrents (prohibits) to the regeneration of pulp tissues.

Calcium Hydroxide vs Dentin Bonding Agents

Clinical success of direct pulp capping with adhesive resins following traumatic pulp exposure and exposure during excavation of carious dentin have been described. In a clinical study of 64 cases of direct pulp capping with a dentin bonding agent following exposure during removal of carious dentin, it was reported that 60 of the teeth were vital 1 year later. In this same study, the pulps of six caries-free third molars were intentionally exposed with a bur, capped with a dentin bonding agent, and the teeth extracted up to 1 year later for histologic evaluation. All cases revealed dentin bridge formation and no inflammatory changes in the pulp.

Calcium Hydroxide vs Dentin Bonding Agents

A number of in vivo studies counter the claims of success of direct pulp capping with adhesive sealers. The animal studies showing successful direct pulp capping with dentin bonding agents are invariably accomplished in an environment not contaminated by bacteria. When the exposed pulps of experimental animals were intentionally contaminated to simulate the clinical setting, the majority of direct pulp caps accomplished with adhesive sealers failed (7.5%), with resulting pulpal death or failure to form dentin bridges; most of the contaminated pulps capped with calcium hydroxide succeeded (77%). Several human studies have confirmed the superiority of calcium hydroxide to adhesive resin sealers for direct pulp capping. One study showed mixed results with pulp capping using a dentin bonding agent. Two other studies showed no evidence of dentin bridge formation in the exposures capped with adhesive resin, while all of the calcium hydroxide-capped pulps demonstrated repair and dentin bridge formation.

Calcium Hydroxide vs Dentin Bonding Agents

Although clinical success has been reported for direct pulp capping with dentin bonding agents, most of these recommendations are empirical and are based on case reports. In an animal study comparing direct pulp capping with a conventional and a visible light-activated calcium hydroxide to direct pulp capping with a dentin bonding agent, dentin bridges formed in almost all pulps capped with $Ca(OH)_2$, whereas dentin bridges formed in less than 25% of the pulps capped with dentin bonding agents. Several other in vivo studies have shown very high failure rates using adhesive sealers for pulp capping, especially compared to calcium hydroxide.

Calcium Hydroxide vs Dentin Bonding Agents

Additional concerns regarding pulp capping with dentin bonding agents is provided by laboratory studies. In vitro microleakage tests showing imperfect seals with dentin bonding agents have been criticized as being invalid because many dye tracer molecules are orders of magnitude smaller than the oral bacteria that cause pulpal inflammation. These tests, therefore, may not be reliable indicators of the ability of bacteria to penetrate dentin toward the pulp. In addition, the outward flow of dentinal fluid in vivo partially opposes the diffusion of toxins into dentin, and those toxins that ultimately reach the pulp are diluted and removed by the circulation. However, while pathogenic intraoral bacteria may be larger than the initial interfacial gaps associated with dentin bonding agents, key components of pulpal inflammation are bacterial by-products, the molecules of which are much smaller than the bacteria.

Calcium Hydroxide vs Dentin Bonding Agents

Interconnecting microporosities within the hybrid layer, created by dentin bonding resins in the demineralized dentin surface, have been shown to be permeable to very small molecules via "nanoleakage.“ This demonstrates the potential for diffusion of even smaller water molecules, which could then lead to the hydrolysis of exposed collagen fibers within the hybrid layer. Likewise, nearly all dye molecules are at least as large as, if not larger than, glucose, which allows for the possibility that bacteria present in the smear layer or in caries-affected dentin could be sustained by the diffusion of this nutrient source. Finally, gap formation seen at the tooth-restoration interface in a number of studies indicates the presence of openings considerably larger than bacteria, viruses, and endotoxins. It would seem reasonable to assume that dye penetration between dentin and the bonding resin would indicate an imperfect seal, ultimately leading to bacterial penetration, especially as the size of the interfacial gap and subsequent leakage is increased by thermal stress.

Calcium Hydroxide vs Dentin Bonding Agents

There are additional concerns regarding indirect and/or direct pulp capping using dentin bonding resins. Numerous studies have found a significant loss of bond strength of adhesive resins to human carious dentin vs sound dentin, leading to further questioning of the integrity of the bond and subsequent ability to prevent bacterial invasion of a carious substrate. Proponents of the use of dentin bonding agents for direct pulp capping point to the shortcomings of calcium hydroxide in this role, including breakdown when acid etchants are used, dissolution under leaky restorations, interracial failure during amalgam condensation, and the presence of tunnel defects in reparative dentin that remain open from the pulp to the medicament interface, allowing recurring microleakage of bacteria to the pulp. The ultimate failure of $Ca(OH)_2$ is thought to be its inability to provide a long-term seal against microleakage. These are all valid concerns; methods for gaining maximum benefit from calcium hydroxide in direct pulp capping, while compensating for its shortcomings, are described at the end of this chapter.

Calcium Hydroxide vs Dentin Bonding Agents

The success of dentin bonding agents for pulp capping depends on the quality and durability of the bond and requires that their placement has no deleterious effects on the pulp.

Quality and Durability of the Bond

Improvements in dentin bonding agents have been dramatic. However, in vitro research has demonstrated that modern dentin bonding resins leak almost immediately when bonded to superficial dentin. The anatomy of dentin near the pulp can have an even greater adverse impact on bond formation. As dentin nears the pulp, more area of a cut surface is taken up by tubules and less by intertubular dentin. The collagen of intertubular dentin is required for the formation of a hybrid layer or hybrid zone, which is thought to be the primary means by which modern bonding resins adhere to dentin. In addition, the bond immediately adjacent to dentinal tubules is often loose, allowing fluid shift and leakage of substrates due to a cuff of collagen-poor peritubular dentin.

Quality and Durability of the Bond

Bond strengths of dentin bonding agents to surfaces of cut dentin are directly related to the area of sound dentin minus the area of the tubules, since resin tags in the dentin tubules contribute little to the bond strength. It is, therefore, not surprising that dentin bonding agents show a significant loss of bond strength to deep dentin compared to superficial dentin. In addition, the bond degrades with time. This is significant because animal studies of pulpal compatibility are short term (21 to 90 days); studies have not provided long-term in vivo evaluation of the effectiveness of bonding systems as barriers to bacterial penetration.

Effect of Dentin Bonding Agent Application on Pulp

Modern dentin bonding systems require conditioning that removes the dentinal smear layer, usually through acid etching. Acid etching of dentin has been demonstrated in multiple animal studies not to cause pulpal damage. However, removal of the smear layer before placement of a dentin bonding resin and composite restoration significantly increased dentin fluid flow and pulpal nerve firing in dogs. The increased dentin fluid flow that can result from opening the dentinal tubules can also cause fluid contamination, poor bonding, and fluid-filled gaps, which can allow bacterial penetration into dentin tubules if the restorative material provides an imperfect seal.

Effect of Dentin Bonding Agent Application on Pulp

These bacteria and their toxins can progress to the pulp despite the outward flow of dentin tubular fluid. Dentin tubules opened by acid etching have been shown to allow the passage of adhesive sealer particulates into the human dental pulp, eliciting foreign body responses that inhibit dentin bridge formation. Finally, applying acid to exposed pulps tends to increase bleeding, which inhibits good adhesion to dentin adjacent to the exposure.

Effect of Dentin Bonding Agent Application on Pulp

Another issue in placing bonding resins directly on pulpal tissue is heat generation from the curing light. An intrapulpal temperature increase of more than 20ºF (11.2ºC) has been shown to cause irreversible damage in vivo. A recent study investigated the temperature rise in a bonding resin during light polymerization. An increase of 18.2ºC was found with a 10-second cure, and a 25.2ºC increase was detected with a 20-second cure. Because most bonding resins require a 20-second cure, there is potential for the pulp to be exposed to dangerous heat levels.

The Future of Direct Pulp Capping Materials

A number of materials are being investigated for future use as direct pulp capping agents. Hydroxyapatite elicited a better pulpal response than calcium hydroxide in one animal study, because the hydroxyapatite acted as a scaffold for dentin formation. Another material that has shown promise is mineral trioxide aggregate (MTA), a combination of tricalcium silicate, tricalcium aluminate, tricalcium oxide, and silicate oxide. This material demonstrates a high pH similar to calcium hydroxide, exhibits compressive strength comparable to reinforced zinc oxide-eugenol, and is radiopaque. It also displays some antibacterial activity and has shown significantly decreased microleakage compared to amalgam and two temporary restorative materials (Super-EBA [Harry J. Bosworth] and IRM [Caulk/Dentsply]). Most important, MTA has been shown to stimulate dentin bridge formation in primate animal studies. The primary disadvantage demonstrated to date with MTA is its extended setting time of 2 hours, 45 minutes.

Antibacterial Efficacy of Restorative Materials

One of the keys to any successful restoration, but particularly for a tooth that has undergone a pulp capping procedure, is the ability to exclude bacteria and their by-products from entry into the pulp.7,38 Of concern are the cariogenic bacteria, since they tend to invade the interface between the restoration and the cavity preparation. Ultimately, these bacteria may lead to recurrent caries, and, if they reach the pulp in sufficient quantities, they will cause inflammatory and ultimately pathologic responses. In particular, Streptococcus mutans is often used in in vitro studies evaluating the efficacy of restorative materials against bacteria, since this organism is associated with recurrent caries

Antibacterial Efficacy of Restorative Materials

The discussion so far has focused on the materials placed immediately adjacent to the site of near or actual pulp exposure. However, the seal provided by the restorative material will also affect the ultimate success of the procedure. Restorative materials can effectively prevent bacterial contamination by one of two means: by providing an impermeable seal with the cavity walls to physically exclude bacteria and the toxins they produce, or by possessing antibacterial properties to destroy bacteria entering the restoration-tooth interface. No material yet provides an impermeable seal that can ensure the physical exclusion of bacteria.

Amalgam

Although typically not considered a material possessing antibacterial properties, dental amalgam has demonstrated varying levels of antibacterial activity. This activity has been attributed to a variety of elements released from amalgam, including copper, mercury, zinc, silver, and chloride compounds. A number of studies have shown that amalgam is effective against cariogenic bacteria, including S mutans, Actinomyces viscosus, and Lactobacillus spp.

Amalgam

S. mutans thrive and produce lactic acid in an acidic environment. The tooth-amalgam interface has a decreased pH, which results in demineralization of tooth structure. In vivo studies have shown that metallic solutions of copper, silver, and zinc are all capable of reducing acid production in plaque. In one case, ions of these metals reduced acid production more than did fluoride in a comparable concentration. All of these ions are released by amalgam and would, therefore, be present at the tooth-restoration interface.

Amalgam

In addition to its antibacterial properties, amalgam is the only restorative material in which the marginal seal improves with time. This is due to the acidic environment and low oxygen concentration that exists in the amalgam-to-cavity wall gap, which promotes corrosion. In conventional amalgam, the gamma-2 phase forms SnO_2, $SnCl_2$, and $Sn(OH)_2Cl$, which slowly fill the interfacial gap. In high-copper alloys, in which there is no gamma 2, the eta phase (Cu_6Sn_5) corrodes to form CuO_2 and $CuCl_2$, but this occurs much more slowly. Corrosion in high-copper alloys may take twice as long as in conventional alloys to produce the same level of seal.

Glass Ionomer

Glass ionomer has the ability to decrease bacterial penetration. possibly through its fluoride release, initial low pH, physical exclusion of bacteria, or release of a metal cation, Whatever the mechanism, glass-ionomer restorative and liner/base materials inhibit cariogenic bacteria and demineralization at tooth-restoration interfaces. In vivo plaque studies assessing the level of cariogenic bacteria invariably show significantly lower levels of these organisms adjacent to glass ionomer compared to either resin composite or amalgam.

Resin Composite

In contrast to amalgam and glass ionomer, resin composite is most dependent on the formation of an impermeable seal to exclude bacterial penetration. This is because, as shown in in vitro bacterial inhibition studies, there is little, if any, inhibitory effect demonstrated by resin composite against cariogenic bacteria and, therefore, there is little resistance to secondary caries activity. This is true even if a resin composite contains fluoride. In fact, research has indicated that certain monomers released from resin composite actually stimulate cariogenic bacteria growth. In vivo plaque studies have demonstrated that levels of cariogenic bacteria in the plaque present on surfaces of resin composite restorations are significantly higher than on either amalgam or glass ionomer.

Resin Composite

While certain adhesive systems are similar to resin composite in that they demonstrate no bacterial inhibition, is some glutaraldehyde-containing bonding systems have shown an inhibitory effect on cariogenic organisms. As previously stated, the quality and durability of adhesive bonding to dentin is questionable, and an impermeable seal is not achieved. Because resin composite does not have the ability to inhibit cariogenic bacteria, placement of a resin composite restoration with a dentin margin in a tooth that has been treated with pulp capping may decrease the chances of successful treatment.

Summary

1. Most operative procedures are traumatic to the pulp, and the effects are at least somewhat cumulative. Excessive heat and dehydration should be avoided. Questionable teeth should receive pulp vitality testing before undergoing clinical procedures.

Summary

2. Because, in direct pulp capping, no dentin remains between the capping material and the pulp, the problem of exposure of pulpal tissues and surrounding vital dentin to caustic or toxic materials is significant. The effects of thermal and chemical insults are magnified with an exposed vital pulp. Of the current materials available, calcium hydroxide remains the material of choice for direct pulp capping, and it should be used with very specific clinical procedures and excellent isolation. Indirect pulp capping is preferred to direct pulp capping; with proper diagnosis and good clinical procedure, direct pulp capping should rarely be required.

Summary

3. Calcium hydroxide is also the material of choice for indirect pulp capping. If the restoration-to-cavity wall interface is well sealed, calcium hydroxide eliminates or greatly reduces the numbers of vital bacteria in the remaining demineralized dentin. Dentin bonding resins adhere poorly to carious dentin, provide a poor seal, and impart little to no antimicrobial activity.

Summary

4. Drawbacks attributed to the use of calcium hydroxide as a pulp capping agent include dissolution with acid etching, degradation under leaky restorations, and interfacial failure during amalgam condensation. While the most significant drawback of calcium hydroxide is its inability to provide a permanent seal against bacterial invasion, the integrity and durability of the bond achieved with dentin adhesives is questionable as well. Although there is potential as a possible future treatment modality, the lack of long-term documentation of clinical success for pulp capping with dentin bonding resins in controlled clinical trials should be weighed against literature that demonstrates 75% to 90% success for up to 12 years when calcium hydroxide is used.

Summary

5. When $Ca(OH)_2$ is used as a pulp capping material, it should be limited to as small an area as possible, and some method of protecting it should be considered during subsequent restorative procedures. Most of the drawbacks to its use can be overcome by the use of a light-activated form of calcium hydroxide. This eliminates most problems, except microleakage. Another approach is to place a glass-ionomer lining material over the $Ca(OH)_2$. This provides a combination of clinically proven materials associated with clinical success in pulp capping. Calcium hydroxide provides antibacterial properties; glass ionomer provides resistance to acids, condensation pressures, and dissolution, as well as fluoride release and adhesion to tooth structure. A well-sealed restoration should then be placed to further reduce the potential for microleakage and enhance the success of the pulp cap.