

Tooth preparations for complete crowns: An art form based on scientific principles

Charles J. Goodacre, DDS, MSD,^a Wayne V. Campagni, DMD,^b and Steven A. Aquilino, DDS, MS^c
School of Dentistry, Loma Linda University, Loma Linda, Calif., and College of Dentistry, University of Iowa, Iowa City, Iowa

Statement of the problem. No recent literature has reviewed the current scientific knowledge on complete coverage tooth preparations.

Purpose. This article traces the historic evolution of complete coverage tooth preparations and identifies guidelines for scientific tooth preparations.

Material and methods. Literature covering 250 years of clinical practice was reviewed with emphasis on scientific data acquired during the last 50 years. Both a MEDLINE search and an extensive manual search were used to locate relevant articles written in English in the last 50 years.

Results. Teeth should be prepared so that they exhibit the following characteristics: 10 to 20 degrees of total occlusal convergence, a minimal occlusocervical dimension of 4 mm for molars and 3 mm for other teeth, and an occlusocervical-to-faciolingual dimension ratio of 0.4 or greater. Facioproximal and linguo-proximal line angles should be preserved whenever possible. When the above features are missing, the teeth should be modified with auxiliary resistance features such as axial grooves or boxes, preferably on proximal surfaces. Finish line selection should be based on the type of crown/retainer, esthetic requirements, ease of formation, and personal experience. Expectations of enhanced marginal fit with certain finish lines could not be validated by recent research. Esthetic requirements and tooth conditions determine finish line locations relative to the gingiva, with a supragingival location being more acceptable. Line angles should be rounded, and a reasonable degree of surface smoothness is desired.

Conclusion. Nine scientific principles have been developed that ensure mechanical, biologic, and esthetic success for tooth preparation of complete coverage restorations. (J Prosthet Dent 2001;85:363-76.)

CLINICAL IMPLICATIONS

The principles identified in this article can help dentists design, assess, and modify complete coverage tooth preparations to ensure clinical success for the treatment of a variety of unprepared and previously prepared teeth.

In 1747, Pierre Fauchard described the process by which roots of maxillary anterior teeth were selected for the restoration of single teeth and replacement of multiple teeth. Gold or silver pivots (posts) were retained in the roots with the use of a heat-softened adhesive called "mastic," and crown replacements were attached to the pivots.¹

In 1766, Adam Anton Brunner described a method

of applying pivot teeth by screwing the pivot into the base of a crown, then enlarging the root canal enough to tightly embrace the root portion of the pivot.² Early "pivot" crowns in the United States used seasoned white hickory wood for pivots.³ Moisture would swell the wood and restrain the pivot.² Subsequently, pivot crowns were fabricated with a combination of wood and metal and then durable all-metal pivots. Metal pivot retention was achieved with threads, pins, surface roughening, and split designs that provided mechanical spring retention.²

With the use of pivots, replacement crowns were made from bone, ivory, animal teeth, and sound natural tooth crowns.² These natural substances gradually were replaced by porcelain. Porcelain pivot crowns were described in 1802 by Dubois de Chemant and became the preferred method for replacement of artificial teeth.²

Clinical tooth preparations for pivot crowns focused

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^aDean and Professor, Department of Restorative Dentistry, School of Dentistry, Loma Linda University.

^bDirector of Graduate Prosthodontics and Professor, Department of Restorative Dentistry, School of Dentistry, Loma Linda University.

^cProfessor, Head and Graduate Director, Department of Prosthodontics, College of Dentistry, University of Iowa.

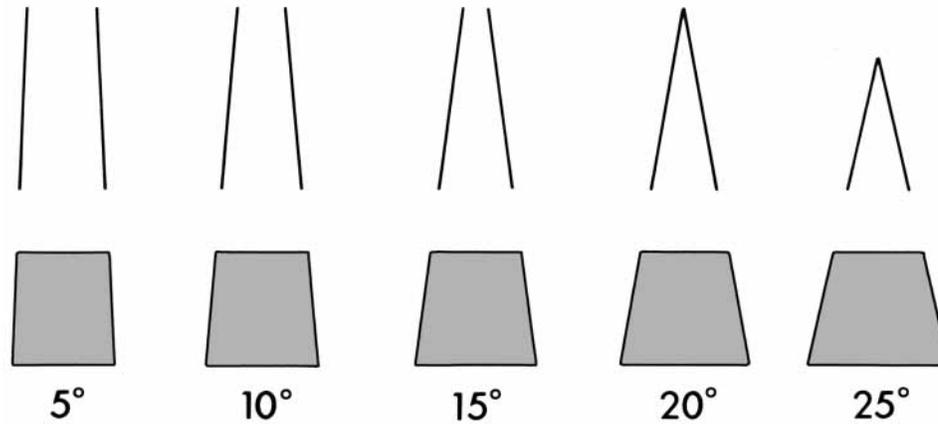


Fig. 1. Diagram with associated *vertical lines* representing total occlusal convergence (TOC) of axial walls when prepared with 5-, 10-, 15-, 20-, and 25-degree TOCs.

on removal of residual coronal tooth structure with saw blades, excising forceps, and files, followed by formation of post spaces with broaches, burs, or spiral drills.^{2,3}

When Charles Henry Land developed his technique for fabrication of porcelain jacket crowns, a change was required in the guidelines to prepare teeth because coronal tooth structure was preserved for crown retention and pulpal vitality retained. He advocated porcelain jacket crowns because they preserved tooth structure,⁴⁻⁶ were more esthetic than pivot crowns,⁴ and reduced the number of tooth fractures associated with combined crown-post restorations.⁷ Land reported less impingement on soft tissue.^{5,6} He also identified the importance of acceptable marginal fit⁶ and indicated that the clinical procedures were less painful to the patient and less fatiguing to the dentist.⁴ Thus, in early publications by Land,⁴⁻⁹ the biologic, mechanical, esthetic, and psychologic advantages of preserving coronal tooth structure and performing conservative tooth reduction were first presented. However, specific details regarding the form of a prepared tooth and written guidelines on tooth preparation were not included in these publications.

During subsequent years, various aspects of tooth preparation design were cited in the literature. The first feature discussed extensively was forms of finish lines. Dr Edward Spalding adopted Dr Land's principles, and they jointly developed the concept of a complete shoulder finish line that provided the all-ceramic crown with uniform thickness and facilitated platinum foil matrix adaptation. Dr Spalding's 1904 article¹⁰ was the first to describe the all-ceramic crown fabrication process in detail and clearly illustrate a shoulder finish line.

In the 1920s and 1930s, articles were published with regard to these relatively new porcelain jacket crowns and the preparation design for the coronal

tooth structure. Considerable focus was still directed toward the most appropriate finish line. Articles were published promoting different variations of shoulder finish lines.¹¹⁻¹⁴ Shoulder finish lines were advocated because of increased restoration strength,¹⁵ porcelain bulk and marginal strength,^{13,16} and fabrication accuracy.¹⁷ Shoulderless tooth preparations with a tapering finish line also were promoted, as were shoulders with a marginal bevel.¹⁸

On the basis of this early dental literature, it was apparent that many persons considered tooth preparations and finish lines important factors that affected the clinical longevity of porcelain jacket crowns.^{11,15,16,19-21} Nevertheless, different opinions existed for the optimal form, and no scientific data were available. The same conditions prevailed as other types of restorations and associated tooth preparations were developed in later years. It was not until the 1950s and 1960s that scientific studies began to analyze tooth preparations and identify features that were essential for success.

This article presents guidelines for complete tooth preparations based on current scientific evidence. Through a review of the dental literature, several critical aspects of tooth preparation have been identified. These critical items warrant discussion so that guidelines that promote the creation of mechanically, biologically, and esthetically sound tooth preparations can be developed.

TOOTH PREPARATION GUIDELINES

1: Total occlusal convergence

Total occlusal convergence (TOC) (the angle of convergence between 2 opposing prepared axial surfaces) was one of the first aspects of tooth preparations for complete crowns to receive specific numeric recommendations. In 1923, Prothero² indicated that "the

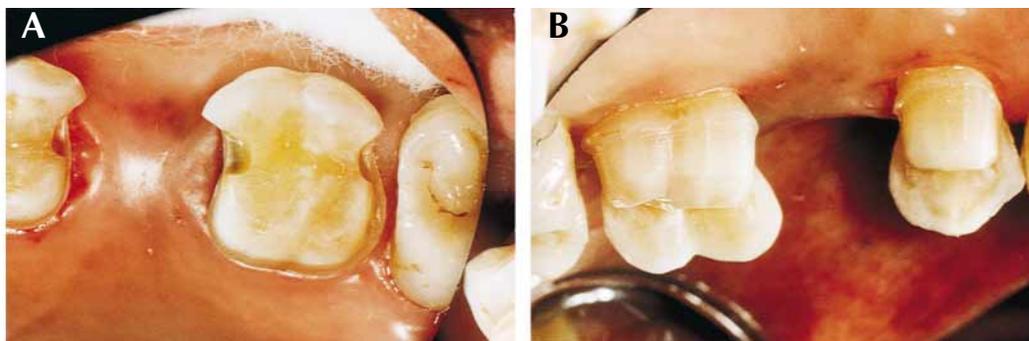


Fig. 2. **A**, Occlusal view of maxillary premolar and molar prepared for partial coverage crowns. **B**, Lingual view of premolar and molar. Note that molar has been prepared with much greater TOC (20 degrees) than premolar (7 degrees). Greater convergence of molar is easier to assess with use of lingual view.

convergence of peripheral surfaces should range from 2°-5°," but more than 30 years would pass before this specific recommendation was subjected to scientific scrutiny. In 1955, Jorgenson²² tested the retention of crowns at various TOC angles by applying a tensile force to a cemented crown. Maximal tensile retentive values were recorded at 5 degrees TOC, supporting earlier 2- to 5-degree recommendations. In addition, other authors²³⁻²⁶ have recommended minimal TOC angles (between 2 degrees and 6 degrees). Wilson and Chan²⁷ reported in 1994 that maximal tensile retention occurred between 6 and 12 degrees TOC.

A critical factor that must be assessed for the development of a guideline for TOC is the actual angle formed when teeth are prepared. Many dentists have assumed that the convergence angles they produce meet the recommended 2- to 6-degree minimal angle. However, it is important to objectively evaluate convergence angles typically established on various teeth. Figure 1 has been created to assist this evaluation process. Placing a prepared tooth die in a position where the axial walls of the die can be superimposed over the lines present in the figure permits close approximations of the TOC.

Occlusal views typically are used clinically to assess TOC but are of limited value for determining the actual convergence angle formed (Fig. 2). Therefore, during clinical tooth preparation, the use of a mirror has been recommended so that a facial or lingual view of the prepared teeth is established. Facial/lingual clinical views are the most effective means of assessing TOC because the convergence of mesial and distal surfaces is readily visible.

It has been determined that dental students, general practice residents, general dentists, and prosthodontists do not routinely create minimal angles such as 2 to 5 degrees²⁸⁻³⁷ (Fig. 3). Studies by Weed et al,²⁸ Smith et

al,²⁹ Noonan and Goldfogel,³⁰ Ohm and Silness,³¹ and Annerstedt et al³² reported mean TOC angles that ranged from 12.2 to 27 degrees, depending on whether the tooth preparations were completed in the preclinical laboratory or in clinical situations. Overall, lower TOC angles were prepared in preclinical situations and during examinations. When tooth preparations by students were compared with those by general dentists, Annerstedt et al³² revealed that the mean TOC for dental students (19.4 degrees) was less than the convergence created by dentists (22.1 degrees). Similar studies have reported mean TOC angles ranging from 14.3 to 20.1 degrees for dentists with no apparent correlation to their level of education or experience.³³⁻³⁷

The dental literature has also presented data on several factors likely to create greater TOC and perhaps even necessitate the formation of auxiliary characteristics that enhance resistance to dislodgment:

1. Posterior teeth were prepared with greater TOC than anterior teeth^{32,33,37} (Fig. 3, A through C).
2. Mandibular teeth were prepared with greater convergence than maxillary teeth.^{29,33,37}
3. Mandibular molars were prepared with the greatest TOC.^{34,37}
4. Faciolingual surfaces had greater convergence than mesiodistal surfaces (Fig. 4).³² However, another study³⁷ determined that mesiodistal convergence was greater than faciolingual convergence.
5. Fixed partial denture (FPD) abutments were prepared with greater TOC than individual crowns.³⁵
6. Monocular vision (1 eye) created greater TOC than binocular vision (both eyes).³⁵ Although it has been demonstrated that binocular vision, at very short tooth-to-eye distances (150 mm or approximately 6 in.),³⁵ causes teeth to be undercut by an average of 5 degrees, teeth are clinically prepared at distances greater than 150 mm even

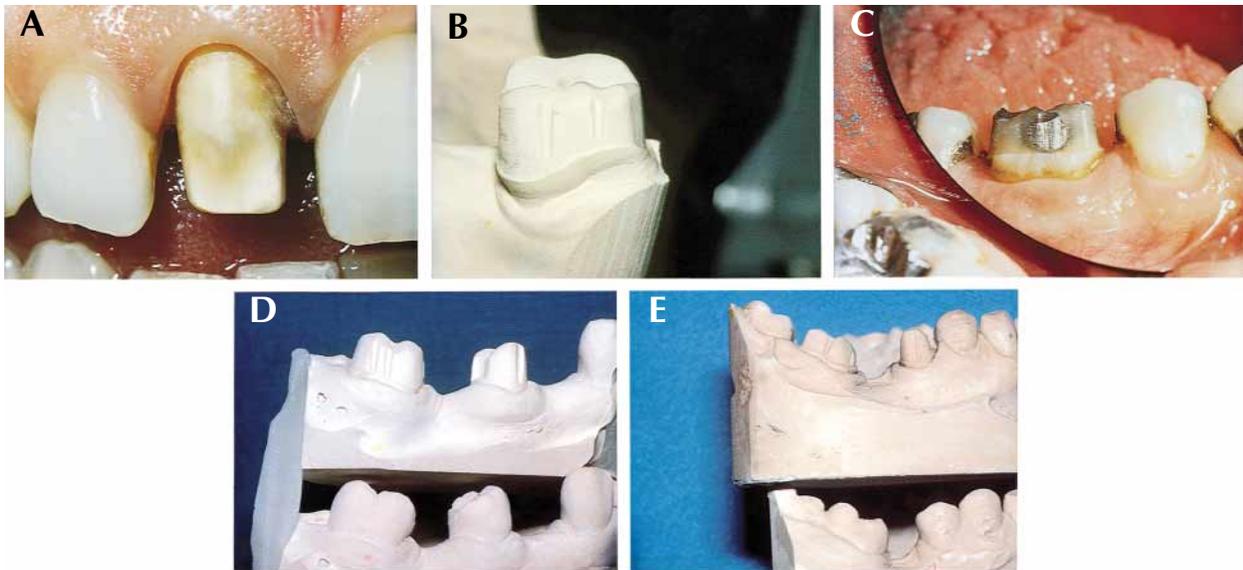


Fig. 3. **A**, Facial view of maxillary central incisor prepared for all-ceramic crown. TOC between mesial and distal walls is 5 degrees. Smallest TOC angles typically are produced on anterior teeth because of their access and visibility. **B**, Cast of mandibular molar prepared with 7 degrees of TOC, representative of smallest TOC angle produced by authors on posterior teeth. **C**, Facial view of mandibular molar with 18 degrees of TOC, representative of many posterior teeth prepared by authors. **D**, Casts of mandibular premolar and molar. Greater convergence was created on less accessible teeth (molars) than on premolars. Premolar TOC is 12 degrees and molar TOC is 22 degrees. **E**, Cast of mesially inclined mandibular molar and resulting tooth preparations. When abutments were moderately to severely malaligned, greater TOC angles frequently were created. Premolar has 18 degrees of TOC and molar has 24 degrees of TOC.



Fig. 4. Occlusal view of maxillary central incisor, canine, and molar prepared for long-span prosthesis. Facial and lingual surfaces of teeth had considerable convergence before tooth preparation; therefore, faciolingual convergence of completed preparations was greater than mesiodistal convergence.

when magnification loupes are used. Therefore, binocular vision has been more likely than monocular vision to create minimal clinical convergence. More recently, resistance to lateral forces and not

retention along the path of insertion has been advocated as the determining factor in a crown's resistance to dislodgement.³⁸⁻⁴⁰ When testing both the retention and resistance of crowns cemented on metal dies, it was concluded that resistance testing was more sensitive than retentive testing to changes in convergence angle.³⁹ Therefore, laboratory tests have become focused on resistance testing through the application of simulated lateral forces.

Dodge et al³⁹ tested the tipping resistance of artificial crowns cemented over teeth with 10, 16, and 22 degrees TOC that were 3.5 mm in occlusocervical dimension and 10 mm in diameter, similar to prepared molars. They reported that 22 degrees of TOC produced inadequate resistance and that there was no significant difference between the resistance of 10- and 16-degree specimens. They concluded that 16 degrees was the optimal convergence angle of the 3 tested because 10 degrees of TOC was not easy to create clinically. Shillingburg et al⁴¹ recently suggested that the TOC should be between 10 and 22 degrees. A guideline for total occlusal convergence should list numeric values that: (1) are achievable in a preclinical laboratory and during clinical tooth reduction, and (2) provide adequate resistance to the dislodgement of restora-

tions when coupled with other tooth preparation design guidelines. Therefore, it is proposed that TOC ideally should range between 10 and 20 degrees.

2: Occlusocervical/incisocervical dimension

Parker et al^{42,43} calculated “critical convergence angles” beyond which a crown theoretically would not possess adequate resistance to dislodgement. In contrast, Wiskott et al^{38,40} determined that a linear relationship exists between convergence angles and a crown’s resistance to dislodgement; they questioned the validity of a critical convergence angle beyond which failure occurs. Recently, Trier et al⁴⁴ tested the concept of a limiting convergence angle by evaluating the resistance form of 44 dies when the restorations had failed clinically through loosening from the prepared tooth. Of the 44 dies, 42 lacked resistance form, supporting a relationship between clinical success/failure and the all-or-none concept of a limiting convergence angle.

The calculations of Parker et al⁴³ with regard to critical convergence indicated that resistance to dislodgement was adequate when a 10-mm diameter molar tooth preparation possessed 3 mm of occlusocervical (OC) dimension and 17.4 degrees or less of TOC. Preparation heights of 1 and 2 mm for a 10-mm diameter tooth preparation required 5.8- and 11.6-degree TOC angles, respectively. Given the typical TOC angles that have been measured from clinical preparations, 17.4-degree TOC appears to be an achievable angle; therefore, 3 mm would be an appropriate minimal OC dimension according to Parker’s calculations.

Maxwell et al⁴⁵ tested the resistance of artificial crowns that were 1, 2, 3, and 5 mm in OC dimension and had minimal (6 degrees) TOC. They concluded that 3 mm was the minimal OC dimension required to provide adequate resistance for crowns made to fit teeth the size of maxillary incisors and mandibular premolars prepared with minimal TOC.

Woolsey and Matich⁴⁶ recorded resistance of uncemented crowns dislodged from dies. Three millimeters of OC dimension was found to provide adequate resistance but only at 10 degrees TOC. However, 3 mm of OC dimension provided inadequate resistance at 20 degrees TOC, an angle frequently formed on many molars. This study supports formation of an OC dimension greater than 3 mm on molars.

Therefore, it is proposed that 3 mm is the minimal OC dimension for premolars and anterior teeth that are prepared within the recommended TOC range of 10 to 20 degrees. Because molars usually are prepared with greater convergence than anterior teeth, have a greater diameter than other teeth, and are located where occlusal forces are greater, 4 mm is proposed as the minimal OC dimension for prepared molars (Fig. 5).



Fig. 5. Occlusocervical dimension of mandibular second premolar and first molar measured with periodontal probe to determine whether 4 mm minimal dimension for molars has been satisfied. Note that prepared proximal wall is only 2 mm high even though facial surface has adequate TOC dimension.

Teeth that do not possess these minimal dimensions should be modified with auxiliary resistance features such as grooves/boxes.

3: Ratio of occlusocervical/incisocervical dimension to faciolingual dimension

The horizontal components of a masticatory cycle and parafunctional habits develop forces on individual crowns and FPDs that are customarily faciolingual (FL) in direction. This dimension of the prepared tooth should be a primary focus of ratio calculations.

When evaluating the resistance of 294 single artificial crowns to dislodgement from their dies, it was determined that 96% of incisor crowns, 92% of canine crowns, and 81% of premolar crowns displayed adequate resistance despite variations in the prepared tooth form and dimensions.⁴⁷ One factor critical to creating this adequate resistance was favorable OC/FL ratios of incisors, canines, and premolars because of their typical anatomic dimensions when prepared (Fig. 6). However, only 46% of molars possessed appropriate resistance. The larger faciolingual dimension of prepared molars compared with other teeth and shorter occlusocervical dimension of many prepared molars compared with anterior teeth and premolars produces a lower ratio and poorer resistance to dislodgement of a molar crown. The greater total occlusal convergence usually formed on molars^{32,33,37} also accentuates the ratio problem.

Theoretical calculations⁴³ indicate that adequate resistance can be achieved with an OC/FL ratio of 0.1 when the TOC is less than 5.8 degrees. A ratio of 0.2 requires the TOC to be less than 11.6 degrees; a ratio of 0.3 requires less than 17.4 degrees of TOC; and a

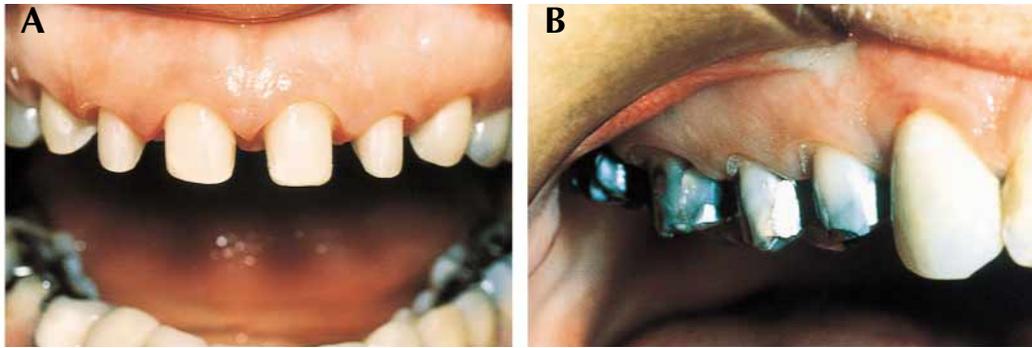


Fig. 6. A, Maxillary 6 anterior teeth prepared for metal-ceramic crowns. After tooth reduction, teeth had favorable ratio of IC dimension to FL dimension due to normal dimensions of teeth before reduction. **B,** Maxillary premolars and molars prepared for metal-ceramic crowns. Note that molars were shorter occlusocervically than premolars due to naturally shorter OC dimension before reduction. Shorter OC dimension of molar teeth coupled with larger FL dimension frequently creates unfavorable OC/FL dimension ratio.



Fig. 7. Three maxillary and 3 mandibular teeth prepared for complete coverage restorations. “Preserved corners” of teeth are particularly evident on 3 maxillary tooth preparations. Shoulder finish lines were used for maxillary metal-ceramic crowns and chamfer finish lines for mandibular all-metal crowns.

ratio of 0.4 provides adequate resistance as long as the TOC angle is 23.6 degrees or less.⁴³

Weed and Baez⁴⁸ presented a diagram for determining the taper ($\frac{1}{2}$ the TOC) of a tooth preparation that provides resistance form based on the occlusocervical/incisocervical (OC/IC) crown dimension and its diameter. To test the validity of the diagram, 50 metal dies were made with 5 different convergence angles and gold copings cast for each die. Inadequate crown resistance was present with a die that was 10 mm in diameter and 3.5 mm in OC dimension and that possessed 22 degrees TOC. This indicated that a 0.35 ratio was inadequate for teeth

with dimensions representative of many prepared molars.

Therefore, it is recommended that the OC/FL ratio should be 0.4 or higher for all teeth.

4: Circumferential morphology

After anatomic reduction, most teeth have specific geometric forms when viewed occlusally. For example, prepared mandibular molars are rectangular in form, maxillary molars are rhomboidal, and premolars and anterior teeth frequently possess an oval form. These geometric shapes have traditionally provided resistance to dislodging forces on individual crowns and FPDs.

Hegdahl and Silness⁴⁹ compared the areas that created resistance form on conical and pyramidal tooth preparations. The pyramidal tooth preparations provided increased resistance because they possessed “corners” when compared with the conical preparations. It is important to preserve the facioproximal and linguoproximal “corners” of a tooth preparation. Teeth that lack natural circumferential morphologic variations after tooth preparation (round teeth) should be modified with the creation of grooves or boxes in axial surfaces. These features can provide resistance to dislodgement while physically engaging the prepared tooth (Fig. 7).

Kent et al³⁷ determined that grooves and boxes, when placed in prepared axial surfaces, had significantly less TOC (7.3 degrees) than the convergence of the axial walls (14.3 degrees) and thereby enhanced resistance form. Molars are usually prepared with greater occlusal convergence than premolars and anterior teeth³³ and possess a shorter occlusocervical dimension than other teeth. Molars also have a less favorable OC/FL dimension ratio. For these reasons, they could benefit from auxiliary tooth preparations. Parker et

al⁴⁷ reported that only 8 of 107 molar dies had grooves and, overall, 54% of the molar castings had inadequate resistance. Therefore, axial grooves or boxes are frequently needed with molars to augment their resistance form.

In addition, research has determined that mandibular molars sometimes are prepared with greater convergence than maxillary molars^{33,37} and that mandibular molars are the teeth prepared with the greatest convergence angles.³⁴⁻³⁷ These data have been linked with increased occlusal forces and mandibular flexion. It therefore is recommended that axial grooves/boxes be routinely used when mandibular molars are prepared for FPDs (Fig. 8).

Resistance to lateral forces commonly is the determining factor in a crown's resistance to dislodgement.³⁸⁻⁴⁰ Horizontal components of masticatory cycles and parafunctional habits direct forces on single crowns and FPDs that are faciolingual in character. Therefore, consideration should be given to the most appropriate location for auxiliary retentive features. Woolsey and Match⁴⁶ determined that proximal grooves provided complete resistance to faciolingual forces, whereas facial or lingual grooves provided only partial resistance to faciolingual dislodgement. Mack³⁵ disclosed that mesiodistal surfaces are prepared with less TOC than faciolingual surfaces; hence, auxiliary grooves in proximal surfaces are more likely to be aligned with the more ideal convergence angles of proximal surfaces. Therefore, auxiliary grooves/boxes designed to augment resistance form should be located on the proximal surfaces of FPD abutments.

5: Finish line location

Many studies have supported the use of supragingival finish lines whenever possible to ensure periodontal health.⁵⁰⁻⁵⁸ However, subgingival finish lines frequently are required for the following reasons: to achieve adequate OC dimension for retention and resistance form; to extend beyond dental caries, fractures, or erosion/abrasion or to encompass a variety of tooth structure defects; to produce a cervical crown ferrule on endodontically treated teeth; and to improve the esthetics of discolored teeth and certain restorations. Studies⁵⁹⁻⁶¹ have indicated that periodontal health can be retained in intracrevicular margins, but it requires properly contoured restorations with satisfactory margins and careful treatment of the hard and soft tissues associated with tooth preparation (Fig. 3, A).

When a subgingival finish line is required, it has been suggested that extension to the epithelial attachment be avoided. Waerhaug,⁶² based on analyses of animal (dog) and human autopsies, indicated that crown margins did not cause pocket deepening if mar-



Fig. 8. Cast of mandibular molar retainer tooth preparation incorporating mesial box to increase resistance form.



Fig. 9. Chamfer finish line formed with tapered round-end diamond instrument. Chamfer finish lines usually are selected for all-metal crowns because they are visually distinct and easy to form. To create chamfer finish line, depth was first established (equaling one-half instrument tip diameter), and that dimension was maintained as instrument was moved around axial surfaces. Chamfer depth of 0.3 mm was desired, so diamond instrument with 0.6-mm tip diameter was used.

gins were at least 0.4 mm occlusal to the base of the gingival crevice. Newcomb⁵⁷ reported that when subgingival margins approached the base of the gingival crevice, more severe gingivitis occurred. Garguilo et al⁶³ proposed that the dimension of the epithelial attachment combined with the dimension of the connective tissue attachment occlusal/incisal to bone should be approximately 2 mm. Cohen and Ross⁶⁴ discussed this relationship and suggested the term *biologic width*. Nevins⁶⁵ indicated that placement of a restoration into this zone could compromise periodontal health. Carnevale et al⁶⁶ extended crown margins to the bone crest in dogs and noted loss of 1.0 mm of crestal bone.

Tarnow et al⁶⁷ placed subgingival finish lines and provisional crowns on 13 teeth in 2 patients. The margins were located half-way between the facial gingival crest and the bone crest. Clinical gingival recession (0.9 mm average with 0.4-1.2 mm range) was observed within 2 weeks, and an average recession of 1.2 mm was recorded within 8 weeks. The histologic analysis indicated that recession mechanisms were activated within the first 7 days, that reformation of the intracrevicular and junctional epithelium occurred, that the reformed junctional epithelium was located apical to the finish line bevel, and that there was crestal bone resorption. Kois⁶⁸ proposed a variation of biologic width that he termed *dentogingival complex dimension* because it included the epithelial attachment, connective tissue attachment, and gingival sulcus depth.

OC variations in finish lines occur on most prepared teeth because of normal changes in the position of a gingival crest around the circumference of teeth. With all-ceramic crowns tested in the laboratory, OC variations in the finish line location have reduced restoration strength.⁶⁹ When gingival position permits, location of the finish lines close to the identical OC locations on all axial surfaces increases all-ceramic crown strengths. Making the proximal finish lines as level as possible faciolingually also reduces stress.⁷⁰ However, these recommendations should be superseded by an intention to minimize subgingival extensions of dental restorations.

Finish lines should be located supragingivally when retention and resistance form, tooth condition, and esthetics permit. When subgingival finish lines are required, they should not be extended to epithelial attachments.

6: Finish line form and depth

All-metal restorations. Chamfer finish lines frequently have been used for all-metal crowns. No scientific studies have stated that chamfers are superior to other finish lines. However, they are used with all-metal crowns because they are easy to form with a tapered, round-end diamond instrument and because they are distinct, being readily visible on the prepared tooth, impression, and die (Fig. 9). Chamfers also possess adequate bulk for restorative rigidity, and their depth is sufficient to permit the development of normal axial contours. Therefore, chamfer finish lines are well suited for all-metal crowns.

Recommended chamfer depth is determined by the minimal metal thickness for strength and minimal space required to develop a physiologic emergence profile. Authors have recommended chamfer finish line reduction depths of 0.3 to 0.5 mm.^{24,26} These recommendations were based on experience in laboratory fabrication of all-metal crowns. To test the validity

of these experience-based guidelines, the faciolingual dimension of 67 wax patterns made on dies with either a feather-edge finish line or a 0.3-mm deep chamfer finish line were measured. The patterns were formed by 57 students and 10 dental laboratory technicians. The dimensions of the wax patterns were compared with the unprepared tooth dimensions. When the 0.3-mm deep chamfer finish line (Fig. 7) was used, the average faciolingual pattern dimension closely approximated the unprepared tooth. The feather edge finish lines produced patterns that were an average of 0.6 mm larger than the unprepared tooth. Therefore, it is recommended that chamfer finish lines for all-metal crowns possess a minimum depth of approximately 0.3 mm.

Metal-ceramic restorations. The following types of finish lines historically have been used with metal-ceramic crowns: chamfer, beveled chamfer, shoulder (Fig. 10), and beveled shoulder. Two initial research articles^{71,72} indicated that when porcelain was fused on metal frameworks, it produced significantly greater marginal metal distortion when a chamfer finish line was used. Although the distortion differences were statistically significant, the clinical relevance could be questioned because the magnitudes of distortion were all less than 50 μm . In addition, subsequent studies failed to show statistical significance. Hamaguchi et al⁷³ recorded no significant difference in marginal metal distortion resulting from the fusion of porcelain when they compared shoulder, shoulder-bevel, chamfer, and chamfer-bevel finish lines. Likewise, Richter-Snapp et al⁷⁴ discovered that finish lines did not significantly affect the fit of metal-ceramic crowns after porcelain fusion. Syu et al⁷⁵ reported no significant differences between the axial and marginal fit of tooth preparations with shoulder, shoulder-bevel, and chamfer finish lines. Belser et al⁷⁶ compared the marginal fit of crowns with a metal shoulder-bevel, a metal shoulder, and a porcelain shoulder before and after cementation. No significant differences were found between finish lines either before or after cementation. Byrne⁷⁷ collaborated the data relative to the effect of cementation and determined that finish line form did not affect the fit of cemented crowns. On the basis of the previously discussed studies, it can be concluded that the selection of finish lines used with metal-ceramic crowns should not be based on marginal fit but on personal preference, esthetics, ease of formation, and the type of metal-ceramic crown (metal marginal collar vs collarless design) being fabricated.

Recommended metal-ceramic finish line depths are based on the minimal material thickness required for strength and esthetics as well as the minimal space required to develop a physiologic emergence profile. Authors^{23-26, 41,78} often have recommended thicknesses between 1.0 and 1.5 mm for the porcelain-veneered marginal area of a metal-ceramic crown. Multiple stud-

ies⁷⁹⁻⁸¹ have indicated that at least 1.0 mm of translucent porcelain (not including metal and opaque) is required to reproduce the color of a shade guide. This research indicates that tooth reductions in excess of 1.0 mm are needed. One study⁸¹ determined that a thickness between 1.4 mm and greater than 2.0 mm of translucent porcelain is needed for metal-ceramic crowns to match the shade guide.

Variations exist between recommended tooth reduction depths and those actually created. One study⁸² of the actual finish line depth prepared on 24 extracted human teeth by 3 dentists discovered a mean shoulder depth of 0.75 mm (\pm 0.17 mm). In addition, 1 researcher measured 34 consecutive dies submitted by students to the in-house dental laboratory for fabrication of metal-ceramic crowns. The mean finish line depth recorded was 0.9 mm with a range of 0.5 to 1.8 mm. These data indicated that finish line depths greater than 1.0 mm were not routinely prepared (Fig. 10).

Although metal-ceramic finish line depths of 1.0 mm or more are recommended, the routinely achievable optimal clinical depth has not been determined.

All-ceramic crowns. All-ceramic crown strengths have been investigated in relation to the finish line. Friedlander et al⁸³ and Doyle et al⁸⁴ measured the strength of all-ceramic crowns made for prepared maxillary premolars with chamfer finish lines, shoulders with sharp axiokingival line angles, and shoulders with rounded axiokingival line angles. The laboratory data with crowns cemented on metal dies showed that crowns with chamfer finish lines were significantly weaker, supporting a similar laboratory finding by Sjogren and Bergman.⁸⁵ However, when all-ceramic crowns were internally etched and cemented on natural teeth with a resinous cement, there was no significant strength reduction in a laboratory study⁸⁶ or in a longitudinal retrospective clinical evaluation⁸⁷ of all-ceramic crowns. Therefore, shoulder finish lines (Fig. 11) are recommended for all-ceramic crowns that are not etched and bonded to the teeth. Either shoulder or chamfer finish lines can be selected for all-ceramic crowns bonded to prepared teeth.

Recommended finish line depths for all-ceramic crowns have ranged from 0.5 to 1.0 mm^{23-26,41,78} (Fig. 11). It has been determined⁸¹ that for the ceramic thickness to match shade tabs, there is limited improvement when thickness of semitranslucent all-ceramic systems (Empress, Ivoclar/Williams, Amherst, N.Y., and InCeram Spinal, Vident, Brea, Calif.) is increased beyond 1 mm. However, with a more opaque system such as InCeram alumina, an increase of ceramic thickness that exceeded 1 mm elevated the shade-matching potential.⁸¹ It has not been advantageous to increase all-ceramic crown finish line depth beyond



Fig. 10. Maxillary canine prepared for metal-ceramic FPD. Shoulder finish line with depth of 0.9 mm. Mesial proximal groove was added to tooth preparation to enhance resistance form because of relatively short lingual wall.



Fig. 11. Maxillary central incisor prepared for all-ceramic crown with use of shoulder finish line with sharp axiokingival line angle. Finish line depth was 0.8 mm.

1 mm with the use of a semitranslucent all-ceramic material.

7: Axial and incisal/occlusal reduction depths

The required depth of reduction varies with different types of crowns and various surfaces of a tooth. Reduction also is affected by the position and alignment of teeth in the arch, occlusal relationships, esthetics, periodontal considerations, and tooth morphology. For instance, a maxillary central incisor with considerable cervical convergence to the clinical crown (viewed facially) requires greater overall proximal reduction during tooth preparation of specific finish line depths than a square-shaped tooth, which has less convergence between the incisal edge and gingiva. Deep occlusal interdigitation of posterior teeth or

appreciable vertical overlap of the anterior teeth often necessitates greater overall reduction of occluding surfaces. Malaligned teeth commonly have required greater reduction of protruding surfaces to permit restoration alignment and/or satisfactory retention and resistance form.

Periodontal health is enhanced through the development of normal cervical crown contours, but overcontoured restorations promote plaque accumulation. Overcontoured restorations can result in periodontal problems, so reduction depth ideally should permit the simultaneous development of normal contours, appropriate esthetics, and adequate strength.

All-metal restorations. Only anecdotal clinical and laboratory experience exists to support proposed reductions of the occlusal and facial/lingual axial surfaces. It is believed that 0.5 to 0.8 mm of reduction near the occlusal surface of facial/lingual surfaces provides sufficient space for the fabrication of all-metal crowns with normal contours and sufficient rigidity to resist flexion from occlusal forces. Experience also indicates that occlusal reduction depths less than 1 mm often compromise occlusal ridge height, fossa depth, and the depth and direction of grooves in the restoration. Underprepared restorations frequently possess relatively flat occlusal morphology, particularly after clinical occlusal adjustment. Although optimal depth has not been identified, experience suggests that axial surfaces should be reduced at least 0.5 mm and the occlusal surface reduced at least 1.0 mm.

Metal-ceramic restorations. For metal-ceramic restorations, textbooks^{23-26,41,78} have recommended reduction of the facial surface between 1.0 and 1.7 mm. One study of extracted teeth⁸⁸ indicated that tooth structure thickness available for reduction varied within each tooth and between different teeth. The maxillary central incisor tooth structure thickness between the pulp and external tooth varied between 1.7 and 3.1 mm.⁸⁸ Data from another study²⁶ indicated that available thickness varies with age. Young central incisors (age 10-19) had a combined facial enamel and dentinal thickness of 1.8 mm, whereas central incisors from 40- to 60-year-old persons had a total thickness of 2.0 to 2.8 mm. El-Hadary et al⁸⁹ measured the tooth structure thickness between the pulp and external surface at the cervical line of premolars. The mean measurements ranged from 2.2 to 2.5 mm for teeth from patients between 25 and 50 years old. Stambaugh and Wittrock⁹⁰ made identical cervical line measurements on 252 extracted incisors, canines, premolars, and molars from patients ranging from 28 to 37 years old. The least amount of mean cervical tooth structure was 2.08 mm for mandibular central incisors. The mandibular first molar exhibited the greatest tooth structure thickness at the cervical line (2.97 mm mean).

These tooth structure thicknesses indicated that certain teeth could withstand 1 to 1.5 mm of reduction, whereas others would have only thin dentin.

The preceding measurements did not, however, consider variations in total occlusal convergence, which result in greater reduction of the incisal/occlusal aspects of the axial surface. This factor could significantly affect proximity of the prepared surface to the pulp. Doyle et al⁶⁹ measured the pulpal proximity when adolescent premolars were prepared with 2 finish line depths (0.8 and 1.2 mm) and 4 total occlusal convergence angles (5, 10, 15, and 20 degrees TOC). A convergence angle of 20 degrees (commonly produced clinically) coupled with a 1.2-mm deep finish line left only 0.3 mm of dentin on certain surfaces of the teeth. With young patients, axial reduction depths in excess of 1 mm can compromise the tooth structure remaining external to the pulp.

Incisal/occlusal reductions of 2.0 to 2.5 mm have been recommended^{23-26,41} for metal-ceramic restorations when restoring these surfaces with ceramics. This thickness is required to develop anatomic form, color, and occlusion. Data^{26,88} on incisal/occlusal tooth thicknesses indicated that more than 4 mm of tooth structure was available even on young central incisors. Mature teeth (age 40-60) had a combined dentinal and enamel thickness range of 6.2 to 6.3 mm. El-Hadary et al⁸⁹ measured the combined enamel and dentinal thickness between pulpal horns and cusp tips and recorded 5.0 to 5.5 mm for premolars. When Stambaugh and Wittrock⁹⁰ recorded the same measurements on all posterior teeth, they reported between 5 and 7 mm depending on which maxillary or mandibular posterior teeth were measured. On the basis of available studies of incisal/occlusal tooth structure thicknesses, it can be concluded that 2.0 mm of incisal/occlusal reduction is achievable, even on the teeth of young patients.

All-ceramic crowns. Malament and Socransky⁹¹ investigated the effect of ceramic thickness on the strength of all-ceramic crowns but were unable to correlate failure of restorations with thickness when the crowns were bonded to prepared teeth with resinous cement. They found no significant differences in the probability of survival after 11.7 years (3430 cumulative monitoring years) between bonded crowns that were less than 1 mm thick and those greater than 1 mm thick. The midaxial thickness of crowns in this study averaged approximately 1.5 mm.⁹¹ Therefore, if the crown is bonded with resinous cement, the reduction should be based on the ceramic thickness required to achieve desirable color and contour.

It has been determined by Douglas and Przybylska⁸¹ that minimal improvement in shade matching occurs when all-ceramic crown thickness is

increased beyond 1 mm with a semitranslucent all-ceramic system (Empress and InCeram Spinell) and a high-value, low-chroma shade such as A1. However, thicknesses in excess of 1 mm are required with the use of more opaque all-ceramic systems or with lower value, more chromatic shades such as C2 and A3.⁸¹ In addition, the inherent color of the prepared teeth can influence the color of overlying all-ceramic crowns, requiring greater ceramic thickness to mask discolored dentin. Therefore, axial reduction for all-ceramic crowns does not need to exceed 1.0 mm when semitranslucent all-ceramic systems are used with higher value, lower chroma shades. It is proposed that incisal/occlusal surfaces be reduced 2 mm because that depth permits the development of normal morphology and has been identified as a safe and reasonable amount to remove from teeth.

8: Line angle form

Line angles are formed when prepared tooth surfaces meet each other. Because sharp line angles create stress concentration,^{70,92,93} it has been recommended that line angles be rounded during tooth preparation to enhance strength. However, the effect of rounded line angles on strength is likely to impact the structural integrity of only all-ceramic restorations. The purpose of rounding line angles with all-metal and metal-ceramic crowns is related more to facilitating laboratory procedures and optimizing fit than to enhancing restoration strength. Round line angles facilitate the fabrication of gypsum casts from impressions without trapping air bubbles as well as the investment of wax patterns without air inclusions. Trapped air bubbles can lead to nodules in castings that impede complete seating of a restoration. Casting nodules also are easier to remove when the line angles are rounded during tooth preparation.

9: Surface texture

Two studies have indicated that tooth preparation smoothness improves the marginal fit of restorations.^{94,95} One article⁹⁶ reported no difference in the marginal seating of complete crowns when axial surfaces were prepared with coarse diamond instruments (120 μm grit size) or with fine diamond (50 μm grit size) instruments.

Smoothness also has an effect on retention but appears to be related to the type of definitive cement used. Two studies^{97,98} demonstrated that roughness did not increase retention with zinc phosphate cement, but several other investigations^{95,96,99-103} discovered that some roughness of tooth preparations improved retention with zinc phosphate cement. In 3 studies,^{95,100,103} roughness did not improve retention with adhesive-type luting agents such as polycarboxy-

late, glass ionomer, and resin; in 3 other studies, roughness did increase retention.^{96,101,102}

Surface roughness generally has been found to improve crown retention with zinc phosphate luting agents. However, the relationship between surface roughness and crown retention has not been definitively determined when adhesive-type cements such as polycarboxylate, glass ionomer, and resin luting agents are used. Therefore, a reasonable degree of smoothness for tooth preparations appears to be beneficial.

CONCLUSIONS

On the basis of the current scientific studies, the following guidelines are proposed for preparing teeth for complete crowns:

1. The total occlusal convergence, or the angle of convergence formed between 2 opposing prepared axial surfaces, ideally should range between 10 and 20 degrees.
2. Three millimeters should be the minimal occlusocervical/incisocervical dimension of incisors and premolars prepared within the recommended 10 to 20 degrees of total occlusal convergence.
3. The minimal occlusocervical dimension of molars should be 4 mm when prepared with 10 to 20 degrees total occlusal convergence.
4. The ratio of the occlusocervical/incisocervical dimension of a prepared tooth to the faciolingual dimension should be at least 0.4 or higher for all teeth.
5. Whenever possible, teeth should be prepared so that the facioproximal and linguoproximal corners are preserved, thereby sustaining variation in the circumferential morphology that enhances resistance form.
6. Teeth without natural circumferential morphology after tooth preparation (round teeth) or teeth that lack adequate resistance form should be modified with the creation of grooves/boxes.
7. Many molars need auxiliary grooves or boxes to enhance resistance form because of their short occlusocervical dimensions and the unfavorable ratio of the occlusocervical dimensions to the faciolingual dimensions.
8. Axial grooves/boxes should be used routinely when mandibular molars are prepared for fixed partial dentures, and they should be located on the proximal surfaces.
9. When tooth conditions and esthetics permit, finish lines should be located supragingivally.
10. When subgingival finish lines are required, they should not be extended to the epithelial attachment.
11. Chamfer finish lines approximately 0.3 mm deep are well suited for all-metal crowns.
12. The type of finish line selected for use with

metal-ceramic crowns should not be based on marginal fit but on personal preference, esthetics, formation ease, and type of metal-ceramic crown. The optimal clinical depth that is routinely achievable has not been determined.

13. Both shoulder and chamfer finish lines can be used with all-ceramic crowns if the crowns are bonded to the prepared teeth. Depths greater than 1 mm are not required when a semitranslucent type of all-ceramic crown is used.

14. Axial and occlusal reductions for all-metal crowns should be at least 0.5 mm deep and 1.0 mm deep, respectively. For metal-ceramic crowns, facial/axial reductions in excess of 1 mm can compromise the remaining tooth structure external to the pulp, whereas 2.0 mm of occlusal reduction is commonly achievable even on a young tooth. With all-ceramic crowns, it is not necessary to exceed 1 mm of axial reduction with semitranslucent systems and higher value, lower chroma shades. Two millimeters incisal/occlusal reduction is recommended for all-ceramic crowns.

15. Line angles should be rounded on all-ceramic tooth preparations to reduce stress in the definitive restoration. With crowns that use metal, the primary purpose of line angle rounding is to facilitate pouring impressions and investing wax patterns without trapping air bubbles and to facilitate removing casting modules.

16. Smooth tooth preparation appears to enhance the fit of restorations. Surface roughness generally increases retention with zinc phosphate cement, but its effect with adhesive cements (polycarboxylate, glass ionomer, resin) has not been as definitely determined. A reasonably smooth tooth preparation is therefore recommended.

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Reprint requests to:

DR CHARLES J. GOODACRE
DEAN, SCHOOL OF DENTISTRY
LOMA LINDA UNIVERSITY
LOMA LINDA, CA 92350
FAX: (909)558-0483
E-MAIL: cgoodacre@sd.llu.edu

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**Noteworthy Abstracts
of the
Current Literature**

Interfacial chemistry of the dentin/adhesive bond

Spencer P, Wang Y, Walker MP, Wieliczka DM, Swafford JR. *J Dent Res* 2000;79:1458-63.

Purpose. This study examined the composition, at the molecular level, of the dentin adhesive/hybrid layer interface formed under wet bonding conditions. It also quantified the diffusion of the single-bottle adhesives into the wet demineralized dentin.

Material and methods. Extracted, unerupted human third molars were obtained. With the use of a low-speed, water-cooled diamond saw, the occlusal one third of the crowns were sectioned perpendicular to the long axes of the teeth. The exposed dentin surfaces then were abraded with 600-grit silicon carbide under water. With a random selection protocol, the specimens were selected for treatment with either Single Bond (3M, St. Paul, Minn.) or One-Step (Bisco, Itasca, Ill.) dentin adhesive. The selected adhesive was applied according to the manufacturer's instructions and polymerized for 30 seconds with a visible light source. Each adhesive group contained 5 tooth specimens that were stored for at least 24 hours in 37°C water. After sectioning the dentin surfaces perpendicular and parallel to the bonded surfaces, the resultant 10 × 2 × 2 mm slabs were mounted, and 3 μ thick specimens were cut from the face of the slabs with a tungsten carbide knife. Differential staining of the specimens was accomplished, and stained sections were dehydrated and examined under a Zeiss light microscope. The exposed protein layer width of each specimen was determined. Slabs were prepared for micro-Raman spectroscopy. Spectra were recorded at multiple sites across the interface of each specimen. Data from the surfaces were compared with reference spectra of pure adhesive, demineralized dentin, and mineralized dentin. Spectra also were collected on a series of model compounds made from type I collagen and adhesive. Relative ratios of the integrated intensities of spectral features from adhesives and collagen were determined. Identical ratios were determined for the interface specimens. These ratios were compared with the calibration curve generated from the model compounds, and a quantitative representation of the percentage of the adhesive as a function of a spatial position across the dentin adhesive interface was determined.

Results. Single Bond adhesive penetration was found to be less than 50% throughout less than half of the hybrid layer; One-Step adhesive penetrated more than 50% throughout most of the hybrid layer.

Conclusion. Results from this investigation provide the first chemical evidence of dentin adhesive phase separation and its detrimental effect on the dentin/adhesive bond. 19 References. —DL Dixon