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Resistance form in tooth preparation

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Retention and resistance form are the properties of a preparation that prevent castings from becoming uncemented, which is one of the top three reasons for the replacement of castings [1,2]. Resistance form is the quality of a preparation shape that prevents rotational movement of the casting about a fixed point [3]. Before cementation, crowns can be tested. Crowns for preparations without resistance form can easily be rolled off the die, whereas preparations with resistance form prevent movement [4,5]. Resistance form is a theoretical concept analyzed in many articles with a mathematical format [3,6–9]. From a clinical viewpoint, resistance form of preparations for which castings were made in a large dental laboratory revealed that most preparations of incisors (96%), canines (92%), and premolars (81%) had resistance form, whereas 46%of molar preparations achieved the desired results [4]. Looking at clinical outcomes, Trier et al [10] found that over 95% of all castings that failed by becoming uncemented lacked resistance form. He also found that 63% of the failures were molars, 35% were premolars, and 2% were anterior teeth. In an up to 15-year outcome assessment of 515 fixed partial dentures (FPDs) whose abutments were tested for resistance form before acceptance for cementation, loss of retention was found to be less common than in other studies. This was attributed to the attention given to establishing resistance form, especially with the use of grooves, before cementation [11]. These clinical results support the basic prosthodontic principle that resistance form is an essential element in preparation design and are consistent with the Caputo and Stanlec [12] statement that resistance form is the most important factor of a preparation for a crown to be successful.

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Guidelines for minimally acceptable preparation taper

Crowns and retainers becoming dislodged is a common problem. A worthy goal is to master the understanding of what clinicians can do to prevent the failure of the dislodged restoration. Guidelines for ideal preparation total occlusal convergence are not consistent and range from 3° [13] to 24° [14]. Measurements of the mean taper of actual clinical preparations have been reported in the range of 25° to 30° [15,16], indicating that approximately half of the measured preparation tapers exceeded these mean values. In a 1986 article Owen [17] concluded, "Most teeth are prepared with tapers greater than 12 degrees and still function adequately. It is not known what retentive figure is the minimum required clinically." The answer to the question of finding guidelines for minimally acceptable taper was provided by applying a unique property of resistance form. Retention and resistance form are dependent on taper. Retention increases as taper decreases [18,19], but the curved graph gives no clue as to minimal acceptability; it shows only that less taper is better in that it provides more retention. Resistance form, on the other hand, exhibits an "on" or "off" nature that is ideally suited for finding minimal acceptability [8,9]. A crown rolls off the die easily or does not move. Envision a mental experiment evaluating the resistance form of a molar preparation with a 10-mm base and a height of 4 mm as the preparation convergence angle is increased from 0°. With parallel sides, the preparation has resistance form and continues to have it as the taper is increased up to a point. At that specific taper, the preparation resistance form switches from "on" to "off." All tapers larger than this dividing point taper do not provide resistance form, and all values less do provide resistance form. With the premise that an acceptable taper must provide resistance form, this dividing point taper makes a reasonable choice for minimal acceptability. Preparations with increasing taper are illustrated in Fig. 1. The first five preparations (A through E) have resistance form, whereas the second five preparations (F through J) do not (the Zuckerman circle and the Lewis perpendicular, which are discussed below, illustrate that preparation F does not have resistance form). For these preparations with the given height and base, the minimally acceptable taper based on principles of resistance form is the taper of preparation E.

Resistance form can be evaluated at one point on a preparation at a time (unlike retention, which requires area for evaluation). The dividing point between tapers that do and do not provide resistance form has been defined as the limiting taper. It has been shown to equal the arctan(h/b), where h is the projected height of the point and b is the projected base relative to the center of rotation on the opposite margin. The h and b do not refer to the height and base of the preparation. It also can be expressed as the arctan(y/x), where (x,y) is the Cartesian coordinate of the point being evaluated and the coordinate system origin is the center of rotation on the opposite margin. It is easier to achieve resistance form on the portion of the tooth

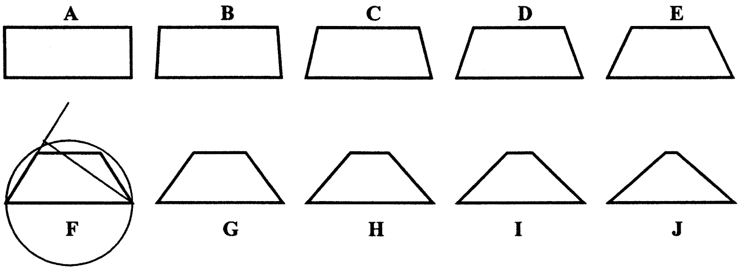

Fig. 1. The "on/off" nature of resistance form as a function of taper. Preparation tapers increases from *A* to *J*, all of which have the same base width and preparation height. Preparations *A* through *E* have resistance form, whereas preparations *F* through *J* do not (the Zuckerman circle and the Lewis perpendicular illustrate that preparation *F* does not have resistance form). Therefore, for these preparations with the given height and base, the minimally acceptable taper is the taper of preparation *E*. The minimally acceptable taper is the dividing point between tapers that do provide resistance form and those that do not.

where y is large (near the occlusal surface) and x is small (near the center of rotation). Points on a groove nearer the center of rotation and higher on the preparation provide resistance form more easily (with larger tapers) than what is required for points lower and farther from the center.

The on/off nature of resistance form can be applied to the average taper of the entire preparation (not limited to straight preparation walls but valid for any shape with even or symmetrical margins), and that value is defined as the limiting average taper [9]. It is mathematically determined to equal 0.5 arcsine (H/B), where the H and B refer to the height and base of the preparation. The total convergence angle is twice this value. By calculating the average height-to-base ratio of preparations of incisors, canines, premolars, and molars, minimally acceptable guidelines for preparation tapers by tooth group were determined. The values expressed as total occlusal convergence were found to be 58° for incisors, 66° for canines, 20° for premolars, and 16° for molars. These values are based on resistance form recommended for minimally acceptable average tapers (ie, the boundary of unacceptability to avoid). Resistance form is easily obtained on anterior teeth, although it is more difficult to obtain with posterior teeth because they are shorter and wider, making the height-to-base ratio less. When a loose retainer is found for an FPD extending from a molar to a premolar, in this author's experience it is usually the molar retainer that is loose. The tooth group order from largest recommended taper to smallest recommended taper is opposite that given by Shillingburg [14]. His recommended values for average ideal tapers (total convergence angle) increase from anterior (10°) to posterior (19° to 22°). Clinically, resistance form being more difficult to achieve for molars is consistent with the finding that over 50% of molar preparations evaluated from a large laboratory lacked resistance form [4] and the type of casting that most commonly comes loose is the molar [10].

It is the molar preparation that must be approached with the most caution to ensure that resistance form is always obtained.

Methods to analyze resistance form

Lewis and Owen [3] showed that for preparations with straight walls, the dividing point between the resistive and nonresistive sections of a preparation wall is the point of intersection with the perpendicular line from the center of rotation on the opposing margin. Consider the side of a preparation to be evaluated as part of an infinitely long line. From the opposing margin, extend a perpendicular to this line. Depending on the taper and shape of the preparation, the point of intersection may be gingival or within or occlusal to the preparation side being evaluated. All points occlusal to the point of intersection have resistance form, and all points gingival do not. If the point of intersection is on the extended line above or occlusal to the top of the preparation, the preparation lacks resistance form. The Lewis and Owen method of evaluating resistance form of side AC is applied by extending a perpendicular line to side AC from the center of rotation E at the opposite margin (Fig. 2). The intersection of the Lewis line and side AC is point B, so all points occlusal to B (segment BC) are resistive and all points gingival to B (segment AB) are not resistive.

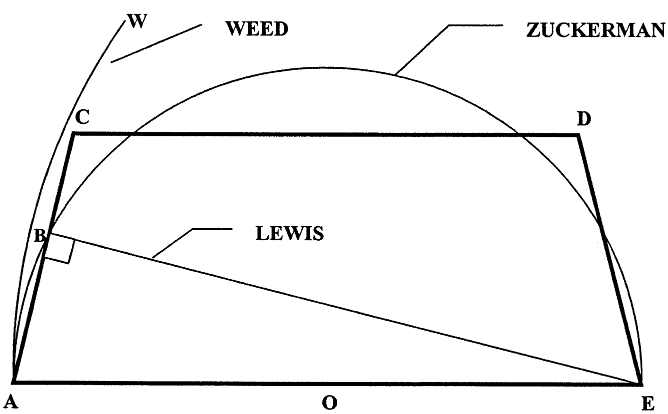

Fig. 2. Three techniques for evaluating the resistance form of side AC. The Lewis method of evaluating resistance form of side AC is applied by extending a perpendicular line to side AC from the center of rotation E at the opposite margin. The intersection of the Lewis line and side AC is point B, so all points occlusal to B (section BC) are resistive and all points gingival to B (section AB) are not resistive. The same results are obtained with the Zuckerman circle, where all points outside of the circle (section BC) are resistive and all points inside (section AB) are nonresistive. The Weed technique predicts that all points on side AC are not resistive because they are inside the Weed circle. This contradicts the Lewis and Zuckerman results, indicating that the Weed hypothesis is not valid.

Weed and Baez [7] presented a method using a boundary circle centered on the opposing margin to evaluate an opposing wall (see Fig. 2). Their hypothesis was that if the intersection of the taper line (side of the preparation) with the horizontal height line falls inside of the circle, it indicates lack of resistance form. Points of the preparation outside of the circle have resistance form. They incorrectly concluded that their hypothesis was valid; it identifies tapers as being nonresistive that in fact provide resistance form [8]. Using an ingenious application of geometry, Zuckerman [20], similar to Weed, used a boundary circle but centered his circle at the center of the base of the preparation with a radius one half of the base radius used by Weed. The points of the side of the preparation within the circle are nonresistant, whereas all points on the preparation wall that are outside of the circle provide resistance form. Because the Weed and Zuckerman circles are different, the techniques are contradictory. Zuckerman's result is consistent with the mathematical derivation of Lewis and Owen and has a mathematical basis for acceptance. Weed concluded that a 3.5-mm high preparation with a 10-mm base would lack resistance form with a convergence angle of 22° (total occlusal convergence of 44°). Using Zuckerman's diagram, the formula for the limiting taper is 0.5 Arcsine (2H/B), which gives 22.2° (total occlusal convergence of 44.4°); 22° falls in the resistive area. The occlusal half of the preparation wall that falls within Weed's boundary circle is above the intersection with the perpendicular line used in the Lewis method for evaluating resistance form. This reveals a contradiction and indicates an error in the Weed method for determining which tapers are adequate to provide resistance form.

The resistance form at each point also can be evaluated by drawing a "direction of arc" arrow, which is an arc of the circle centered on the opposite margin [8]. At the point being evaluated, if the direction of the arrow is into the preparation, that point has resistance form; if it is away from the preparation, it does not. This technique can be used to evaluate all preparation shapes, not just straight-walled preparations. Because all direction of arcs on the same radius line of concentric circles are parallel, comparing the direction of arc at a point on any radius line of any circle (centered on the opposite margin) with the preparation reveals whether the direction is away from or into the preparation wall. In Fig. 2, by visualizing the direction of arc provide by the Weed circle (which is centered on the opposite margin), from A to B the direction is away from the preparation wall; from B to C the direction is into the preparation wall. This supports the fact that all points on the wall from B to C are resistive, contradicting Weed's results.

Laboratory studies evaluating resistance form

Laboratory studies evaluating resistance form of cemented castings as a function of taper have resulted in a linear relation between the variable measured and taper. Weed [7] used an Instron (Instron Corp., Canton, Massachusetts) machine to force cemented castings from metal dies, and Wiscott [21] developed a cyclic testing apparatus measuring the load level at which 50% of the samples survived 10^6 stress cycles. Both studies produced linear results with no sudden drop observed in the load level required to dislodge the crowns as taper was increased. These results seem to contradict the on-off nature of resistance form. Based on his results, Wiscott states that the concept of limiting taper expressing itself clinically as an all-or-nothing phenomenon is unrealistic [21], but one would not expect to see the on/off nature of resistance form expressed if only preparations having resistance form in the "on" category were evaluated. That is what happened in both studies. For a symmetrical straight-walled preparation with 10° of total occlusal convergence (5° axial inclination on each side) to lack resistance form, its height would have to be less than 0.7 mm, less than any die studied by Wiscott. Therefore, all samples had resistance form, and no on/off boundary effect was seen. It is difficult to make a symmetrical straight-walled die lack resistance form. For example, the limiting taper for a symmetrical 4-mm-high, 10-mm-wide preparation equals 0.5Arcsine2H/B or 26.6°, for a total occlusal convergence of 53.2°. This may seem excessive, but it is more challenging to achieve the resistive tapers with the clinical preparations of teeth than it is in the lab with a lathe-cut metal die.

There are clinical preparations that lack resistance form [4]. One must be wary of uneven margins, which can make a preparation with parallel walls (0° taper) lack resistance form (Fig. 3) [8]. Rounding of sharp occlusal surfaces is another factor that increases the likelihood that clinical preparations will lack resistance form. These factors are commonly seen in the preparation of tipped molars. The tapers used in lab studies may be more consistent with ideal recommended guidelines than what is achieved clinically. Students attempting to meet a 12° criterion did not result in achieving that goal [22]. Realizing and accepting that much larger preparation tapers are seen clinically than normally are advocated as standards should allow us to examine larger tapers for lab studies to explore the on/off nature of resistance form. The studies must ensure that there are preparations in the "on" and "off" categories. A clinical study of crowns that have failed by dislodgment reveals that almost all failures are on preparations lacking resistance form, supporting the premise that a reasonable standard for acceptable preparation taper is that it provides resistance form [10]. It also supports the premise that a relationship exists between clinical success/failure and the all-or-none nature of resistance form.

Methods to enhance resistance form

Preparation modifications to provide resistance form to a nonresistant preparation include crown lengthening, shoulder preparation, proximal box or groove, occlusal isthmus, and pins or posts [20]. Grooves provide a marked

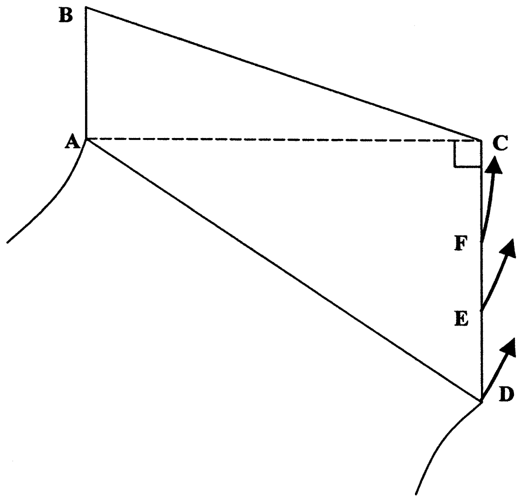

Fig. 3. A diagrammatic representation of the preparation of a tipped mandibular molar that has perfectly parallel mesial and distal walls with a total occlusal convergence angle of 0°. There is no resistance form at any point on the mesial wall (even though it is longer than the distal wall). This is illustrated by the three "direction-of-arc" arrows moving away from the wall at points D, E, and F (with center of rotation the opposing margin A). It is also illustrated by the Lewis method that says all points below point C lack resistance form because that is the intersection of the perpendicular radius from the center of rotation (point A). For the mesial wall of this preparation, there is no possible adequate preparation taper to provide resistance form. Buccal or lingual grooves must be used to ensure this preparation has resistance form.

increase in measured resistance values in laboratory studies [16,23]. An interesting aspect of the groove is that if the direction of rotation arcs away from one wall of the groove, it must arc into the other wall, so it provides resistance coming or going (Fig. 4). To ensure resistance form on molar preparations, grooves should be used routinely [4]. In preparing the walls of the tooth, care must be taken to ensure there are no undercut margins. Considerable preparation taper is required, especially in the molar region, to assure that margins are not undercut and that common draw is achieved by being able to visualize all preparation walls. In contrast, grooves can be placed with almost no fear of undercuts. Because the margins are not involved, any undercuts that are accidentally produced can easily be waxed out in the lab and do not cause a problem. It is far better to place grooves on a routine basis in molar preparations to ensure resistance form and deal with the possibility of undercuts when and if they occur. Because theoretically only one point is needed to provide resistance form [8], short grooves can be effective. The groove can be envisioned as having three walls, so a groove on the buccal surface has a mesial, distal, and lingual surface providing resistance to mesial, distal, and lingual rotation. To obtain the benefit of the lingual wall, it is necessary to hold the bur in the line of draw and not lay it against the side of the preparation, which may be more tapered. The tooth

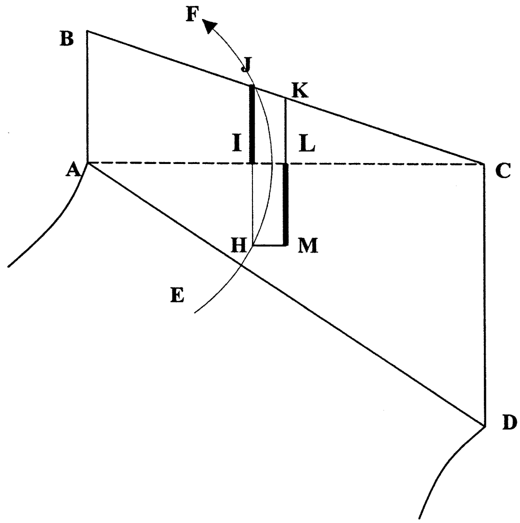

Fig. 4. Adding a groove (HIJKLM) to the preparation in Fig. 3 affects the resistance form. Where the direction of arc arrow from E to F is away from one wall of the groove, it directs into the other wall so that one of the two opposing walls provides resistance form at each level. For the portion of the groove below the center of rotation, it is the mesial wall of the groove that has resistance form (indicated by the heavy line from L to M). For the portion of the groove above the distal margin, it is the distal wall of the groove from I to J that is resistive.

structure in which the groove is placed is expected to withstand torquing forces to prevent crown rotation, so it must be structurally sound. In placing grooves, look for and use sound tooth structure.

Summary

Clinical evidence indicates that resistance form is one of the essential elements in crown preparation design to ensure clinical success. The on/off nature of resistance form lends itself to the theoretical determination of minimally acceptable tapers. The boundary between resistive and non-resistive tapers can be determined at each point on a preparation (limiting taper) or for the entire preparation (limiting average taper). Using average height-to-base ratios for incisor, canine, premolar, and molar preparations, minimally acceptable guidelines can be determined for symmetrical preparations. The short wide molar with the small height-to-base ratio is the most difficult tooth preparation to achieve resistance form, and grooves should be used routinely. The average guidelines for taper do not apply to preparations with uneven margins, which are frequently seen with tipped mandibular molars. It is possible to have perfectly parallel opposing mesial and distal walls and not have resistance form. Buccal and lingual grooves solve the problem. Every tooth must be analyzed individually. The Lewis, Zuckerman and "direction of arc" techniques for evaluating resistance form are consistent, but the results do not agree with those of the Weed method. Laboratory studies have produced a linear relation between measured failure loads and taper but have failed to provide tapers in the "off" region of resistance form. Thus, the relation of failure load to taper has not been evaluated over the "on or off" boundary. It is anticipated that in properly designed laboratory studies the continued linear relationship will not be seen across this boundary and that adding grooves to nonresistive preparations will require much larger loads to produce failure. The clinical data indicate that there is a relationship between clinical success or failure and the on/off nature of resistance form.

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