RESEARCH ARTICLE

Volumetric analyses of restorative crown preparations in simulated-premolar and -molar teeth

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Abstract
Crowns or abutments of fixed partial denture tooth preparations to restore natural teeth or implant-supported restorations require tooth or abutment reduction in a tapered format. Low angulations of axial wall taper to the long axis of the tooth or abutment have been shown to increase the restoration's stability during masticatory function with large occlusal loads. The tooth preparation and luting agent stabilize the restoration during these loading cycles to prevent dislodgement. Restoration dislodgement represents a catastrophic failure of the prosthesis in function. The preparation attributes contribute to prevent displacement failure and reduce luting agent tensile and shear stresses. Low axial wall taper levels increase resistance to rotational displacement. Increasing axial wall angulations produces negative consequences including reduced rotational resistance, reduced surface area and increased volume of remaining tooth structure. These three considerations have been shown to involve three variables: preparation vertical height, horizontal base width from rotational axis and rotational axis vertical height compared to the opposing axial resisting wall. Natural tooth preparations are completed by a restorative dentist with a hand-held high-speed handpiece with cutting instruments within the oral cavity; while implant-supported custom abutments are prepared in a similar manner but machined outside the oral cavity. As a result, the machined abutment is more controlled for ideal taper in inanimate materials compared to the intraoral tooth preparation on human vital tissues. This experimental study will analyze the preparation of simulated-vital tooth premolars and molars for volume loss at ideal and non-ideal axial wall angulations with variation of vertical heights and vital pulpal tissue volumes.

Keywords: rotational resistance form, fixed restoration stability, premolar- & molar-sized tooth model, preparation volume loss, supplemental groove

1.1 Introduction

Natural tooth preparation for single-crowns or fixed partial denture (FPD) abutments on vital teeth within the oral cavity are accomplished by the restorative dentist with a high-speed handpiece and tapered rotary burs. The clinician attempts to maintain the bur's orientation parallel to the long axis of the tooth to produce a tapered preparation within a narrow range of accepted guidelines to accomplish what is called "the ideal preparation." These ideal levels of tooth preparation taper have been established at 2-to-6° per axial wall, also known as the convergence angle with 4-to-12° with the sum of two opposing wall taper angles. Historically, this range of ideal wall taper angles has been thought to maintain internal tooth attributes which have been designed to counter rotational displacement of the restoration in function. [1-4]

In a classic review of the literature,[5] the authors proposed the use of grooves & boxes to supplement short or overly tapered axial taper angles; in addition, these authors established minimum vertical preparation heights of 3-mm or greater in premolar teeth and 4-mm or greater in molar teeth. Numerous investigative studies have evaluated various aspects of rotational restoration displacement over a span of years from 1960's to the present. [6-38] Rotational displacement has been thought to be countered by both the axial wall attribute and the luting agent. The axial wall attributes at ideal levels have been proposed to reduce the stress on the luting agent by physical barriers to restoration rotation. [21, 32]

Some experimental studies have elaborated on these guidelines to reveal three additional variables that impact the ability of the axial wall to block rotational displacement. These variables include axial wall vertical heights,[19, 29, 33] rotational axis height located opposite the axial resisting wall[30] and the horizontal width between the resisting axial wall and the rotational axis location.[38] In general, the maximal allowable taper angulation of the axial resisting wall is lower if the rotational axis is higher in vertical location compared to the opposing wall's restorative finish line and at greater horizontal width distances of larger tooth forms, *i.e.*, molars compared to premolars.[30]

In addition, another factor for consideration is the surface area of the preparation. As axial wall tapers get larger, experimental studies have shown that the surface area gets smaller.[33] This correlation has been thought to impact the luting agent-tooth surface contact with larger tooth surface area being desirable. A tooth preparation factor that has not been experimentally studied is the tooth preparation's volume reduction compared to its original unprepared condition. As the axial wall taper angulations increase, a n increase in tooth volume might be proposed as a hypothesis. In other words, tooth preparation volume loss will be proposed to increase as axial wall taper angles increase. The purpose of the present investigation is to evaluate the amount of tooth volume loss at both ideal and non-ideal increasing axial wall angulations with & without supplemental grooves.

1.2 Method

The experimental analysis utilized geometric figures of varying dimensions to simulate two types of posterior teeth, mandibular 2nd premolar and maxillary 1st molar. These two tooth forms were simulated by cubes of known dimensions, 6- x 6-mm horizontal mesial-distal and bucco-lingual widths in a simulated-mandibular premolars and 9- x 9-mm horizontal mesial-distal and bucco-lingual widths in simulated-maxillary molars. Each of these tooth forms were varied in vertical height at 3-, 4-, 5-mm in the premolar and 4- & 5-mm in the molar simulated-tooth forms. These geometric forms were selected to simulate these two tooth forms so mathematical analyses with geometric & trigonometric calculations could be accomplished.

1.2.1 Independent & Dependent Variable Data:

The volume loss from the pre-preparation state to the prepared state in each category served as the dependent variable data of interest throughout the study. The dependent variable data, volume loss, was reported as mm^3 lost as well as a percentage (%) of the volume lost from original pre-preparation volume. The prepared tooth form with all four axial walls angled at the same taper levels in degrees, °, to the long axis; the following levels of axial wall taper served as four independent variable data categories: 2 & 6° as two "ideal" categories and 12 & 16° as two "non-ideal" categories.

Additional independent variable data in the tooth model included three levels of vertical preparation height categories, standardized supplemental grooves and two sizes of pulp chamber volumes; the vertical height categories in the two tooth models were: premolar 3-, 4-, 5-mm and molar 4- & 5-mm.

1.2.2 Geometric & Trigonometric Calculations:

The volume of the pre-preparation premolar & molar as square cubic or rectangular cubic tooth forms was calculated as units in cubic millimeters (mm^3) according to the following formula:

base width (mm) x base length (mm) x vertical height (mm).

The preparation of the cubic tooth form had four equal axial wall angulations to form a truncated pyramid with a flat occlusal table; the volume of the truncated pyramid was determined by calculating the volume of a large pyramid then calculating the volume of the smaller, upper pyramid. The volume of the truncated pyramid, as the simulated-tooth preparation, was determine by subtracting the volume of the smaller upper pyramid from the larger pyramid. The formula for calculating volume of the large & small pyramids was:

$^{1}/_{3}$ *x base width (mm)x base length (mm) x perpendicular height of pyramid (mm).*

The determination of volume loss from tooth preparation was determined by subtracting the truncated pyramid volume from the pre-preparation cube volume in mm^3 and as a percentage of original volume loss from the original, pre-preparation volume. The geometric analyses were standard formula for volume calculations for cubes & right pyramids.[39]

The volume of supplemental grooves was determined by sequence of trigonometric calculations, starting with the formula of a right cone:

$^{1}/_{3}$ *x* π *x* r^{2}*(mm) x base length (mm) x perpendicular height of pyramid (mm).*

This calculation began with the computation of a right cone as an extension of a 172-tapered bur extrapolated to a full-sized right cone based of taper angle and diameter of the bur tip, 1.18mm. The total volume of the groove in each tooth form & tapered axial wall angulation was determined in a series of geometrical component-steps with trigonometric formulas. These component steps were determined with the use of circles, rectangles, squares, and right triangles with two known values to compute a third unknown value with trigonometric or geometric formula calculations. These components within the groove preparation are illustrated in Fig. 2.

Figure 1.1 Illustration of pyramids with right triangles used to calculate volume of truncated lower-pyramid which represented the simulated-premolar and molar tooth forms in this experimental study.

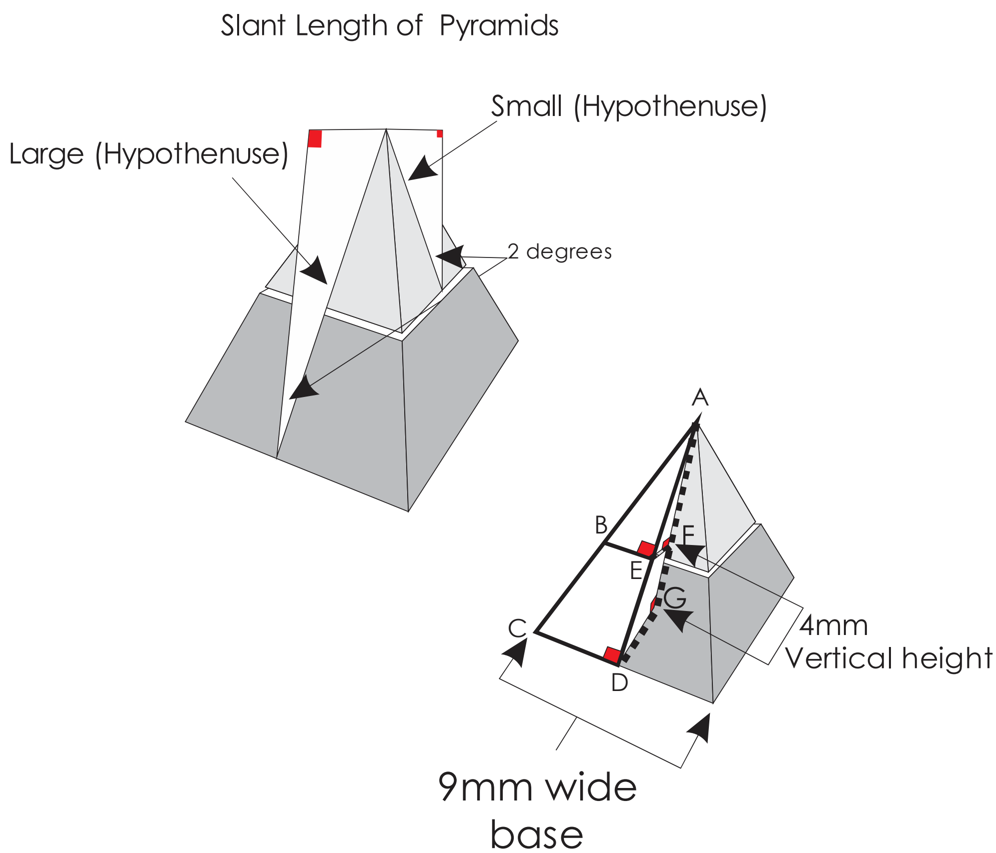
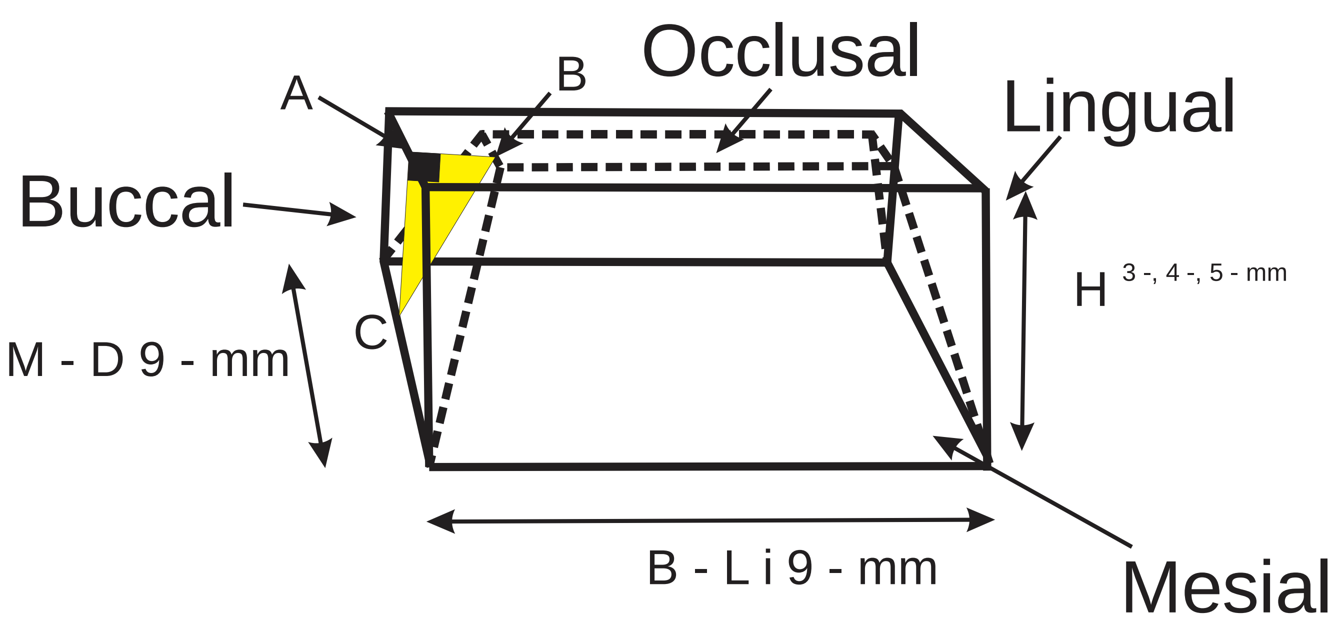


Figure 1.2 Illustration of preparation of cubic figure to form a truncated pyramid with right triangles used to calculate volume loss from preparation of axial walls.



1.3 Results

1.3.1 6-mm x 6-mm Premolar Tooth Form, 3-, 4- & 5-mm Vertical Height Categories (Table 1.1)

The dependent variable data, volume of loss due to axial wall preparation only, in this tooth form with 3-mm vertical preparation height, revealed preparation tooth volume loss in the range of 3.7 to 26.5mm^3 with 3.7 & 10.6mm^3 in the 2 & 6° ideal categories and 20.3 & 26.5mm^3 in the 12 & 16° non-ideal categories. As a percentage volume lost, values of 3.4, 10.9, 18.8 & 20.9%, respectively, were found. The total volume loss in this tooth size due to supplemental grooves was 13.1, 14.7, 17.2 &18.9mm^3 in the respective axial wall taper categories. The total preparation volume loss due to both axial wall & groove preparations were 15.5, 23.4, 36.3 & 42.1%.

Table 1.1 Premolar-size Tooth Form 6- x 6-mm Volume Data in mm^3 & %-loss

	Axial Wall Angulation Categories			
Vertical Preparation Height Categories				
3-mm 2º	6º	12º	16º	
Total Volume Lower Truncated Pyramid	104.3	97.4	87.7	81.5
Original Square Cube 6- x 6- x 3-mm	108.0	108.0	108.0	108.0
LOST VOLUME Axial Wall Preparations	3.7	10.6	20.3	26.5
%Axial Wall LOSS from Original	**3.8%**	**10.9%**	**18.8%**	**20.9%**
2-Groove Volume	13.1	14.7	17.2	18.9
Axial+2-Grooves %VOLUME LOSS	**15.5%**	**23.4%**	**36.3%**	**42.1%**
4-mm	2º	6º	12º	16º
Total Volume Lower Truncated Pyramid	137.5	125.2	108.1	97.4
Original Square Cube 6- x 6- x 4-mm	144.0	144.0	144.0	144.0
LOST VOLUME to Preparation	6.5	18.8	35.9	46.6
%Axial Wall LOSS from Original	**5.7%**	**16.5%**	**30.6%**	**39.5%**
2-Groove Volume	16.0	18.9	23.5	26.5
Axial+2-Grooves %VOLUME LOSS	**15.6%**	**26.2%**	**41.2%**	**50.8%**
5-mm	2º	6º	12º	16º
Total Volume Lower Truncated Pyramid	169.8	150.4	123.8	107.7
Original Square Cube 6- x 6- x 5-mm	180.0	180.0	180.0	180.0
LOST VOLUME 4-Axial Walls	10.2	29.6	56.2	72.3
%Axial Wall LOSS from Original	**5.7%**	**16.5%**	**31.2%**	**40.2%**
2-Groove Volume	19.2	24.0	31.2	36.2
Axial+2-Grooves %VOLUME LOSS	**16.4%**	**29.6%**	**48.0%**	**59.6%**

The dependent variable data, volume of loss due to axial wall preparation only, in this tooth form with 4-mm vertical preparation height, revealed preparation tooth volume loss in the range of 6.5 to 46.6mm^3 with 6.5 & 18.8mm^3 in the 2 & 6° ideal categories and 35.9 to 46.6mm^3 in the 12 & 16° non-ideal categories. As a percentage volume lost, values of 4.5, 13.1, 24.9 & 32.3%, respectively, were found. The total volume loss in this tooth size due to supplemental grooves was 16.0, 18.9, 23.5 & 26.5mm^3 in the respective axial wall taper categories. The total preparation volume loss due to both axial wall & groove preparations were 15.6, 26.2, 41.2 & 50.8%.

The dependent variable data, volume of loss due to axial wall preparation only, in this tooth form with 5-mm vertical preparation height, revealed preparation tooth volume loss in the range of 10.2 to 72.3mm^3 with 10.2 & 29.6mm^3 in the 2 & 6° ideal categories and 56.2 & 72.3mm^3 in the 12 & 16° non-ideal categories. As a percentage volume lost, values of 5.7, 16.5, 31.2 & 40.2%, respectively, were found. The total volume loss in this tooth size due to supplemental grooves was 19.2, 24.0, 31.2 & 36.2mm^3 in the respective axial wall taper categories. The total preparation volume loss due to both axial wall & groove preparations were 16.4, 29.6, 48.0 & 59.6%.

1.3.2 9-mm x 9-mm Molar Tooth Form, 4- & 5-mm Vertical Height Categories (Table 1.2)

The dependent variable data, volume of loss due to axial wall preparation only, in this tooth form with 4-mm vertical preparation height, revealed preparation tooth volume loss in the range of 9.8 to 70.8mm^3 with 9.8 & 28.3mm^3 in the 2 & 6° ideal categories and 54.2 & 70.8mm^3 in the 12 & 16° non-ideal categories. As a percentage volume lost, values of 3.0, 8.7, 16.7 & 21.8%, respectively, were found. The total volume loss in this tooth size due to supplemental grooves was 16.0, 18.9, 23.5 & 26.5mm^3 in the respective axial wall taper categories. The total preparation volume loss due to both axial wall & groove preparations were 4.9, 14.6, 24.0 & 30.0%.

Table 1.2 Molar-size Tooth Form 9- x 9-mm Volume Data in mm^3 & %-loss

	Axial Wall Angulation Categories			
Vertical Preparation Height Categories				
4-mm	2º	6º	12º	16º
Volume Large Pyramid	3479.3	11567.0	571.6	423.7
Volume Small Upper Pyramid	3165.1	860.3	301.8	170.5
Total Volume Lower Truncated Pyramid	314.2	295.7	269.8	253.2
Original Square Cube 9- x 9- 4-mm	324.0	324.0	324.0	324.0
LOST VOLUME to Preparation	9.8	28.3	54.2	70.8
% -LOSS from Original	**3.0%**	**8.7%**	**16.7%**	**21.8%**
2 LOST VOLUME 2-Grooves	16.0	18.9	23.5	26.5
% -TOTAL VOLUME LOSS	**4.9%**	**14.6%**	**24.0%**	**30.0%**
5-mm	2º	6º	12º	16º
Volume Large Pyramid	3479.3	11567.0	571.6	423.7
Volume Small Upper Pyramid	3089.7	795.3	301.8	170.5
Total Volume Lower Truncated Pyramid	389.6	360.7	320.4	294.7
Original Square Cube 9- x 9- 5-mm	405.0	405.0	405.0	405.0
LOST VOLUME to Preparation	15.4	44.3	84.6	110.3
% -LOSS from Original	**3.8%**	**10.9%**	**20.9%**	**27.2%**
LOST VOLUME 2-Grooves	19.2	24.0	31.2	36.2
% -TOTAL VOLUME LOSS	**8.5%**	**16.9%**	**28.6%**	**36.2%**

The dependent variable data, volume of loss due to axial wall preparation only, in this tooth form with 5-mm vertical preparation height, revealed preparation tooth volume loss in the range of 15.4 to 110.3mm^3 with 15.4 & 44.3mm^3 in the 2 & 6° ideal categories and 84.6 & 110.3mm^3 in the 12 & 16° non-ideal categories. As a percentage volume lost, values of 3.8, 10.9, 20.9 & 27.2%, respectively, were found. The total volume loss in this tooth size due to supplemental grooves was 19.2, 24.0, 31.2 & 36.2mm^3 in the respective axial wall taper categories. The total preparation volume loss due to both axial wall & groove preparations were 8.5, 16.9, 28.6 & 36.2%.

1.4 Discussion

The literature has cited "ideal" tooth or FPD abutment angulation in the range of 2-to-6º per axial wall, convergence angulations of two opposing walls in the range of 4-to-12º.[5] Goodacre, Aquilino & Campagni[5] have proposed utilization of supplemental grooves to improve tooth preparations with less than ideal axial wall taper angulations. In additional studies, these standards have been shown to be dependent on several factors: vertical preparation height, base width from rotational axis to opposing axial wall, and rotational axis height relative to opposing axial wall restoration finish line height location.

The current investigation has shown tooth volume loss in the "ideal" 2-to-6º, 4-wall axial wall taper category to be in the range of 3 to 17% of original tooth structure volume loss in both tooth form models. This level of tooth preparation volume would be viewed as the most resistance to rotational displacement of the restoration in function without additional adjunctive groove supplementation. However, an ideal preparation in the upper loss range of 17% may have some negative side effects as an insult to pulpal vitality. In a vital tooth, the pulp chamber vitality can be affected by the process of tooth preparation by cutting odontoblastic processes as a type of trauma. In the present investigation, the greatest tooth volume loss of 60% or more than three times greater tooth volume loss was found in the 5-mm vertical height category at 16º with supplemental grooves in the premolar tooth form.

Average pulp chamber volume CT scan data in the literature found in similar human teeth have been found to be 15.7 & 25.0mm^3, respectively. With a pulpal volume of 15.7mm^3, less than 20% of original tooth structure remains to resist functional forces of occlusion or external stress to pulpal tissues. Presumably, adjunctive groove placement in the 16º axial wall taper would be remarkably close to the pulp chamber with approximately 2-mm or less of remaining dentine between the groove and the pulp chamber wall. The pulp chamber size data in this study was obtained in older subjects; generally, pulp chamber size decreased in volume with age due to the odontoblast response to lay down secondary dentine in response to hot & cold foods, functional mastication, tooth wear, etc. As a result, the issue of tooth volume loss with tooth preparation would be especially important in younger patients with an exceptionally large pulp chamber.

In addition to the insult to the vital pulp tissues, tooth preparation removes large amounts of enamel and dentine volume which greatly effects the prepared tooth's ability to resist masticatory forces in function. Studies have utilized FEA to model the restored tooth in response to external loading; [21,22,23,24,26,36] the effect in a single crown on a natural tooth can be seen in Fig. 1.4 from a published study,[36] increasing axial wall taper angles in the restoration-tooth complex caused a type of flexion within the system. This investigation evaluated a simulated restoration on a maxillary premolar tooth; the tooth used in this investigation was an extracted, unblemished premolar tooth from a young adolescent with a large pulp chamber. At exceptionally large convergence angles, the 200N load produced a bending of the tooth with an opening of the marginal restoration finish line area greater than 150µm. Although no supplemental groves were used in this FEA study, the 32º convergence angulation with the greatest displacement values would predict probable tooth volume loss at the maximal 40% found in the present investigation. Thus, 12 & 16º volume loss in both two forms would be expected to follow this detrimental rotational stress pattern in function, *i.e.*, differential preparation bending with marginal restoration opening under inner incline, angled loading.

Figure 1.3 Illustration of groove preparation with 172-tapered bur to determine diameter and groove components used to compute volume loss due to groove placement.

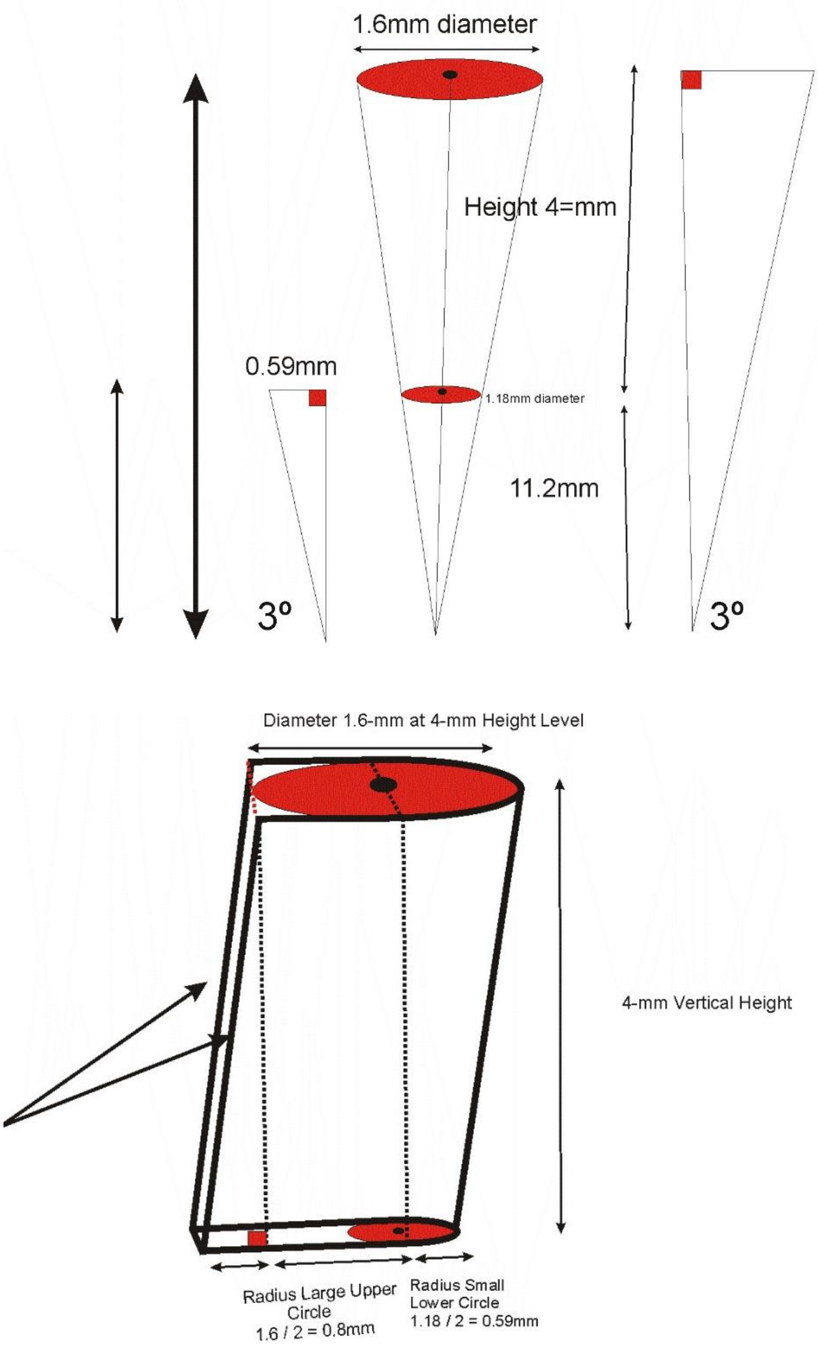


Figure 1.4 Illustration of FEA crown loaded 200N with increasing dentine volume reduction. (With Permission J Prosthodont 2013;22(4):307, Figure 4. [PubMed: 23279111])

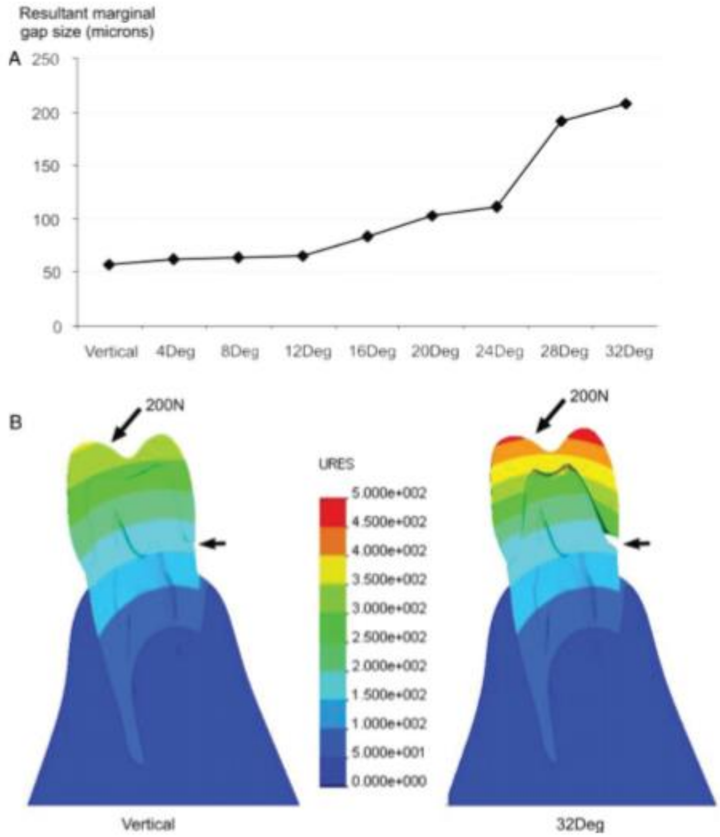


Figure 4 Comparison of calculated resulting displacements (μm) at palatal margin of crown. (A), Section plots. (B), Exemplifying resulting displacement of vertical and 32° model (deformations scale 5×). Note changes in elliptical radius of displacements towards apical as result of tooth flexure.

An additional factor to be considered in the mix is the average clinician's ability to accomplish "ideal" convergence angles in the preparation of a natural tooth. Amongst a large number of studies too numerous to be cited in this manuscript, these two citations demonstrate that both dental students[41] and experienced clinicians[42] do not have the skills to accomplish the ideal standards in everyday tooth preparation. Most can be assumed to attain 12 to 16º axial wall taper in their clinical preparations on patients. According to Goodacre, Aquilino & Campagni,[5] these preparations should employ groove supplementation to improve these deficient preparations. According to the current investigation data, 2-groove supplementation would remove an additional tooth volume in the range of 10-to-37%; these adjunctive procedures may only be needed in situations with deficient axial wall angulations rather than "ideal" axial wall taper levels to avoid over reduction of tooth structure unnecessarily.

Many of these same standards apply to implant prosthodontic restorations in the single crown as well as FPD forms such as minimal vertical height, rotational resistance walls, rotational axis location related to base length and vertical height in even & uneven positions and supplemental groove use. One advantage of implant-retained abutments is the custom abutment can be milled to predetermined axial wall taper angles of the ideal 2-to-6º; supplemental grooves can be used to improve custom abutments, as needed. Another advantage of these type abutments is the modulus of elasticity of the substructure; many of the alloys used for this purpose have a significantly higher modulus of elasticity compared to dentine with a large pulp chamber. Therefore, the abutment would be expected to bend or flex under occlusal load to the same degree as vital dentine in the natural tooth.

In conclusion, the supplemental groove adjunct has been recommended for tooth preparations with the absence of opposing axial wall resistance to rotation; however, in overprepared teeth or abutments with an absence of rotation resistance, groove supplementation increases the total volume loss which significantly impacts the tooth in a negative manner. Based on the results of this investigation, axial wall angulations >6º and the concomitant use of groove supplementation should be avoided, if possible, in vital premolar and molar tooth forms.

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