Original Article

Novel methods reveal that parallelism contributes to the functional vertical slot dimension in ceramic and metal brackets

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ABSTRACT

Objectives: To validate a novel method for measuring the clinically relevant bracket slot and use these methods to test the hypothesis that various metal injection molded (MIM) and esthetic ceramic injection molded (CIM) brackets have a bracket slot accuracy within 1 mil (0.001") of their reported slot dimension.

Materials and Methods: A Nikon iNEXIV-VMA-2520 laser microscope was used to measure slots of six series of CIM brackets and two series of MIM brackets via a vision measuring system of 256 gray levels to capture each edge of the slot, largely taking out human subjectivity. This system had a maximum permissible error of 2 + 8 L/1000 μm with a point resolution of 0.1 μm and was estimated to be more accurate than previous methods by a factor of 10. The video image for each bracket was autofocused by a blinded operator, and 40 point-to-line measurements were calculated along the clinical slot and averaged.

Results: Vertical slot dimension varied from series to series and within the series of brackets. Three of six CIM and two of three MIM brackets had a statistically significant mean slot size 0.001 inches larger than reported. The reported precision of these CIM brackets, as determined from standard deviation, varied from series to series.

Conclusions: A novel system that incorporates parallelism into analysis of vertical bracket slot dimension was described. When the entire clinically relevant slot was considered, MIM and CIM brackets had similar precision but were significantly oversized, with contribution from a nonparallel, likely diverging, vertical slot dimension. (*Angle Orthod.* 2018;88:812–818.)

KEY WORDS: Parallelism; Slot; Brackets; Injection molding

INTRODUCTION

The direct marketing of Invisalign and the development of clear, nonmetallic brackets has dramatically increased patient interest in active-treatment esthetics. There are now almost as many choices for clear brackets as their metal forebearers. These tooth-colored brackets are available in different prescriptions and are primarily made of a poly- or monocrystalline aluminum oxide by the process of ceramic injection molding.

The edgewise orthodontic bracket has evolved over the past few decades to provide a myriad of prescription choices incorporating bracket angulations for each tooth that are based upon different treatment philosophies. The differences in these prescriptions can be measured in a few degrees, and the expectation is that, whatever the manufacturing material utilized, these variations have clinical significance. Previous studies have reported that most metal injection molded (MIM), milled, and cast metal brackets have bracket slot accuracy within 1 mil of their reported slot dimension.[1] Several bracket prescriptions are available with differences that reflect specific treatment philoso-

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phies. For example, the torque built into the maxillary central incisor bracket can vary by up to 15° between two different prescriptions.

A critical factor affecting the expression of a bracket prescription is the accuracy of the bracket slot. Various orthodontic textbooks have defined expectations for bracket slot accuracy. In *Contemporary Orthodontics*, Proffitt et al.[2] stated that the precision of orthodontic bracket manufacturing should render slot dimension accuracy of at least 1 mil to ensure accurate expression of a chosen prescription. Bennett[3] warned that oversized slots defeat the premise of prescription orthodontic brackets as the larger slot size does not allow for complete prescription expression.

Several studies have evaluated the accuracy of slot dimension of maxillary central incisors, as the expression of torque (buccopalatal crown-root inclination) is critical to the successful positioning of the upper anterior teeth. Cash et al.[4] evaluated upper left central incisor metal brackets and found the bracket slots of brackets from 11 bracket series (six different manufacturers) to be all oversized with a range of 5% to 24% larger than manufacturer's specifications. They also found that the slot walls in some bracket systems were either diverging or converging instead of parallel.

Bhalla et al.[5] evaluated upper left central incisor self-ligating metal brackets from six different series (four different manufacturers). They found that the slot dimension of all these bracket groups were between 5% andm15% greater than manufacturers claims and also noted that there were significant differences in bracket dimension of brackets from the same manufacturer.

Brown et al.,[1] in probably the most comprehensive study of bracket slot consistency to date, evaluated five complete cases of metal upper and lower brackets (20 brackets per case) from 10 different bracket series (six different manufacturers) and recorded a single point-to-point measurement, made by line of sight, from a microscope filar measured 100 nm down the slot.[1] They found significant variation in bracket slot dimensions that "would not be able to express given torque without significant wire bending."[1] Unlike Cash et al.[4] and Bhalla et al.,[5] Brown et al. [1] found that this variance included brackets that were both wider and narrower than manufacturers' claims, and that manufacturing anomalies might occur in only one bracket in a series. A lack of parallelism of the slot walls was also a common observation.

Nishio et al.[6] measured the resistance of several series of clear brackets to torsional forces from an archwire. In the course of their study, they measured the slot dimension of 10 upper right central incisor brackets from six representative esthetic bracket types analyzed by a projector profile method, and they observed a range of 0.02232" to 0.02307" with a mean of 0.02258".

The purpose of this study was to measure the slot dimensions of entire sets (20 brackets) from different series of metal and tooth-colored, nonmetallic orthodontic brackets with a critical eye toward the measured slot dimension vs the manufacturer's claim. This deviated from previous methods in that the clinically relevant bracket slot was quantified by a digital process.

MATERIALS AND METHODS

In this study, the following stainless steel bracket series were analyzed: 0.022" Ormco Damon Q (Ormco Corp, Orange, Calif), 0.018" and 0.022" Unitek Victory (Unitek, Monrovia, Calif). In addition, the following ceramic brackets were analyzed: GAC In-Ovation 0.022" (GAC, Bohemia, NY), 0.018" and 0.022" Chic (GC Orthodontics, Alsip, Ill), 0.018" 3M Clarity (3M, Monrovia, Calif), 0.022" Spirit MB (Ormco Corp), and 0.022" Damon Clear (Ormco Corp) (Figure 1). The methods of manufacture were obtained verbally through discussion with company representatives or published sales literature. Brackets of each brand were measured in a series, including lower canine to canine for ceramic brackets.

A single, blinded operator used a Nikon iNEXIV VMA-2520 laser microscope (Nikon, Tokyo, Japan) to measure each series of bracket slots, using a vision measuring system of 256 gray levels to capture each edge of the bracket slot. This system had a $2 + 8$ L/1000 μm with a point resolution of 0.1 μm, which was estimated to be more accurate than previous methods by a factor of 10. As shown in Figure 2, brackets were mounted in rope wax and set by the operator to orient the mesial of the slot to a 90° angle to the microscope table as done previously.[1] As shown in Figure 3, the video image for each bracket was automatically focused on a point on the side of the bracket wing; 40 points on one slot edge were autodetected as a line, and the opposing slot edge was captured as a reference point. Subjective exclusion criteria for slot edge start and stop of both lines and reference points were defined as the beginning and the end of extreme curvatures at the proximal and distal parts of the slot edge. A point to a line measurement was calculated automatically between the 40 points on one slot edge and the line from the opposing edge.

Statistical Analysis

The error of the method was assessed by having the blinded operator measure 10 brackets at two different time points, 30 days apart, with a paired *t*-test suggesting that there was no statistically significant

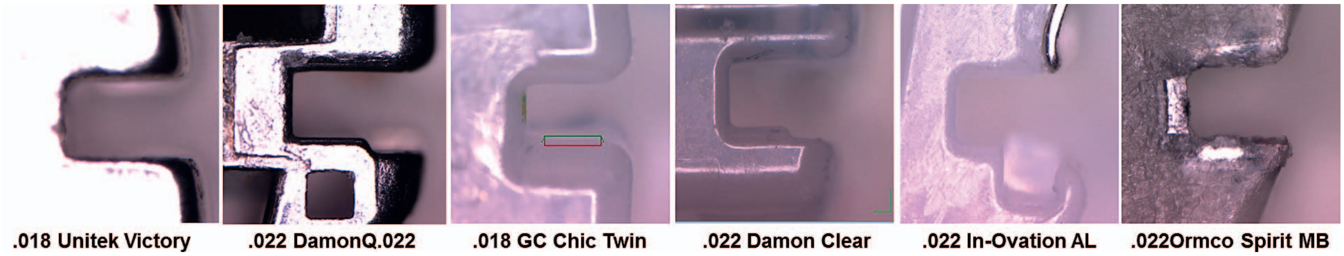

Figure 1. Representative images of several metal injection molded and ceramic injection molded slots under magnification.

difference in measurements between the two time points (0.477).

As in a similar study,[1] a sample size of N = 95 was chosen. A post hoc power analysis was also performed to ensure that enough brackets were examined to detect a minimum difference up to 0.001". Since each bracket system's slot dimension was being compared with a uniform standard (0.018 and 0.022, as appropriate), no between-group multiple comparisons test was conducted. Rather, individual *t*-tests for means were used to compare each system's mean value against the manufacturer-advertised slot dimension.

RESULTS

All of the bracket series measured had mean slot dimensions larger than the manufacturer's stated dimensions, and five series had slot dimensions 0.001" or larger than manufacturers' claims, thus categorizing them as unacceptable to accurately express a given prescription according to current orthodontic teaching.[2,3] The statistics for the measured slot dimensions for the nine different bracket series is found in Table 1, with graphical representation in Figure 4. The 0.018" and 0.022" 3M Victory (MIM), 0.018" GC Chic, 0.018" Unitek Clarity, and 0.022" GC Chic had a slot size statistically 0.001" higher than their reported values ($P < .05$). The 0.018" Unitek Victory had the lowest standard deviation, while the 0.022" Ormco Spirit MB had the highest standard deviation.

When compared with previous results that only used a single point-to-point measurement 100 μm from the depth of the slot,[1] the measurements in this study were far higher when analyzing the same MIM 0.018", 0.022" Unitek Victory and 0.022" Damon Q bracket series as shown in Table 2. These differences were highly statistically significant. The observer in this study was able to measure the brackets with an intraclass correlation coefficient of 0.983, whereas the correlation coefficient from the Brown at al.[1] study was reported to be 0.947.

Similar digital methods were used to quantify bracket slot wall parallelism, which are reported in Table 3, graphed in Figure 5A, and represented by photos in Figure 5B. All brackets measured had a mean slot wall

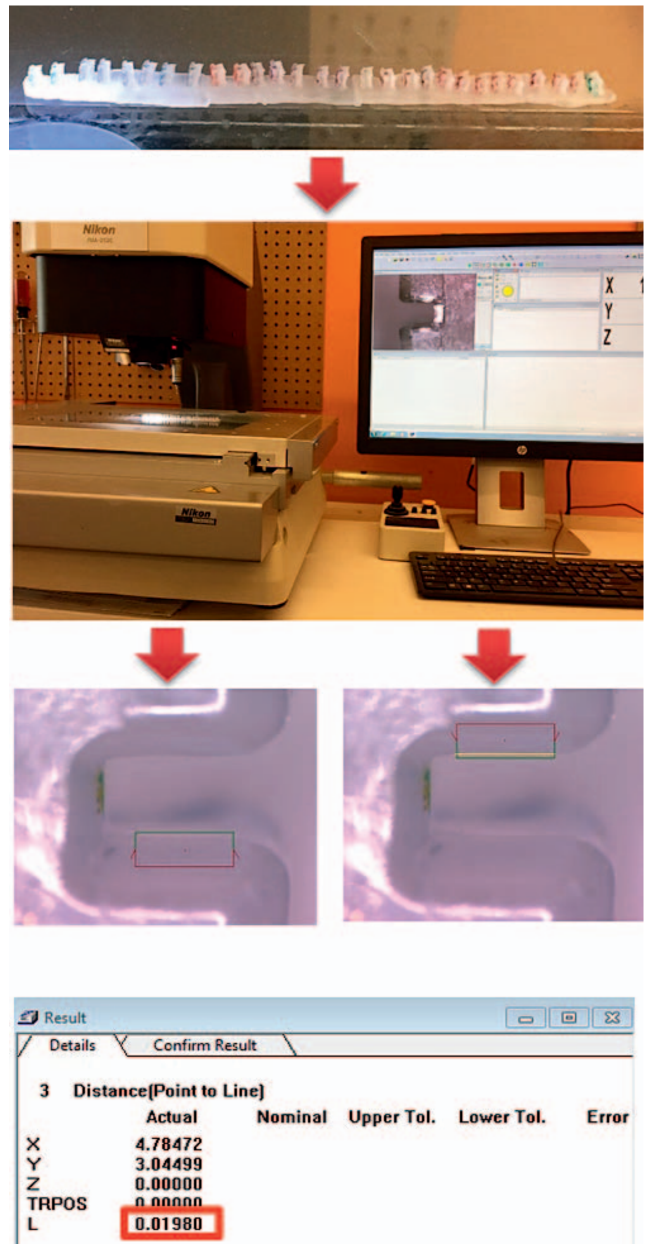

Figure 2. Methods for vertical slot measurement. An observer first orients the brackets in rope wax perpendicular to the slot. A second blinded observer autofocuses the microscope on the slot wall, then autodetects a line on one slot wall and a series of 40 points on the opposing wall. The mean of these 40 point-to-line measurements is recorded.

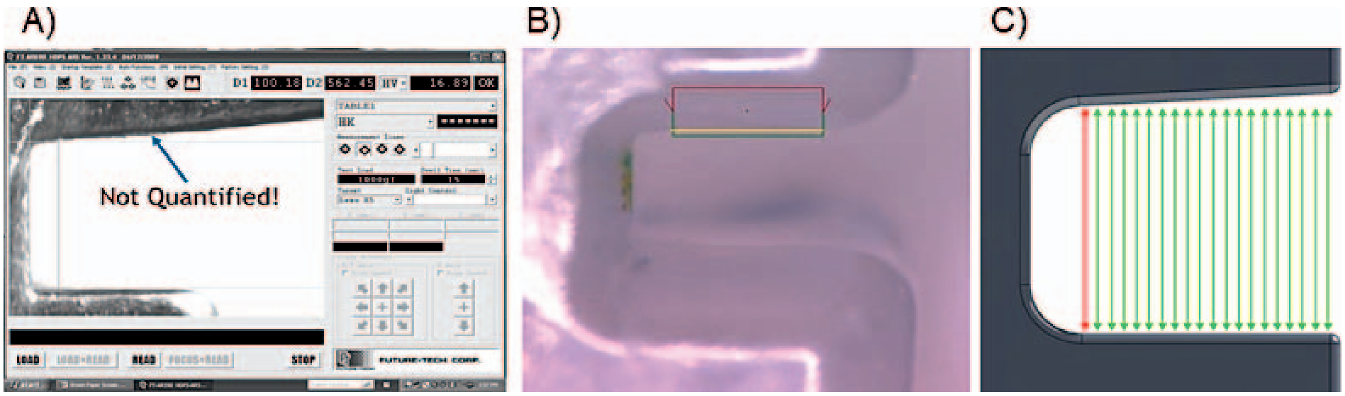

Figure 3. A comparison between current methods and those by Brown et al.[1] (A) Previous methods: Single point-to-point measurement beginning 100 μm from base.[1] (B) Current methods: 40 point-to-line measurements along a flat surface. (C) Current algorithm for data collection incorporates measurements across the functional bracket slot.

divergence of at least 0.5°, though both divergent and convergent slot walls were observed and recorded. Though there are no known existing standards for slot wall parallelism, it can be concluded that the 0.022" Damon clear and the 0.022" Ormco Spirit MB had slot walls that were divergent by more than 1° ($P < .05$). The Ormco Spirit MB had the highest mean divergence, while the 0.022" Damon Clear had the highest standard deviation. An analysis of variance was performed and revealed statistically significant differences in the degree of bracket slot divergence ($P < .0001$). Subsequent Tukey honest significant difference post hoc test revealed that this difference was mainly between 0.022" Damon clear and 0.022" Ormco Spirit MB vs the remaining bracket systems.

DISCUSSION

All of the bracket series measured had mean slot dimensions larger than the manufacturers' stated dimensions. Five series had slot dimensions 0.001" or larger than manufacturers' claims, thus categorizing them as unacceptable according to current orthodontic teaching[2,3] (Figure 4). Possible sources of manufacturing error in MIM and ceramic injection molded (CIM) brackets exist in both the mold for a given bracket and the post-curing phase whereby the green body is fired in a furnace. For this reason, evaluating a series of brackets is more relevant than evaluating a number of brackets for the same tooth, which would likely be derived from the same mold. This approach may be less critical when measuring a milled metal bracket because no molds are used to create the slot.

When comparing the current study to Brown et al.[1], it is important to note the difference in methodology. The three metal bracket series that were measured in the Brown et al.[1] study and in the current study (0.018" and 0.022" Victory [MIM] and the 0.022" Damon Q [MIM]) were vastly larger in the current study (Table 2). After recalibration of the Nikon laser microscope, this observation was confirmed and considered to be due to critical differences in methods.

In the Brown et al.[1] study, a single point-to-point measurement was made by placing a filar 100 μm from

Table 1. Statistics for Results in Figure 4[a]

	0.018" Unitek Victory (MIM)	022" Unitek Victory (MIM)	0.022" Damon Q (MIM)	0.018" GC Chic (CIM)	0.018" 3M Clarity (CIM)	0.022" GC Chic (CIM)	0.022" Ormco Spirit MB (CIM)	0.022" Damon Clear (SL) (CIM)	0.022" Innovation (AL) (CIM)
Number of values	100	73	100	95	97	98	101	73	101
Minimum	0.018	0.02204	0.02176	0.01841	0.01752	0.02233	0.02074	0.0216	0.02154
25% percentile	0.01896	0.02304	0.0227	0.01938	0.01945	0.02336	0.02187	0.02243	0.0228
Median	0.01925	0.02343	0.02308	0.01995	0.01982	0.02379	0.0225	0.02277	0.02298
75% percentile	0.01961	0.02372	0.0236	0.02022	0.02027	0.02452	0.0232	0.02301	0.02332
Maximum	0.02024	0.02403	0.02461	0.0212	0.02109	0.0253	0.0249	0.02387	0.02519
Mean	0.01927	0.02338	0.02312	0.01984	0.0198	0.02393	0.02255	0.02276	0.02302
Standard deviation	0.0004326	0.0004117	0.0006723	0.0005809	0.0006769	0.0007076	0.0008445	0.0004374	0.0004966
Lower 95% CI of mean	0.01918	0.02328	0.02299	0.01972	0.01967	0.02378	0.02238	0.02266	0.02292
Upper 95% CI of mean	0.01936	0.02347	0.02325	0.01996	0.01994	0.02407	0.02272	0.02287	0.02311
Coefficient of variation	2.24%	1.76%	2.91%	2.93%	3.42%	2.96%	3.74%	1.92%	2.16%

[a] CI indicates confidence interval; CIM, ceramic injection molded; and MIM, metal injection molded; SL, self ligating; AL, active ligating.

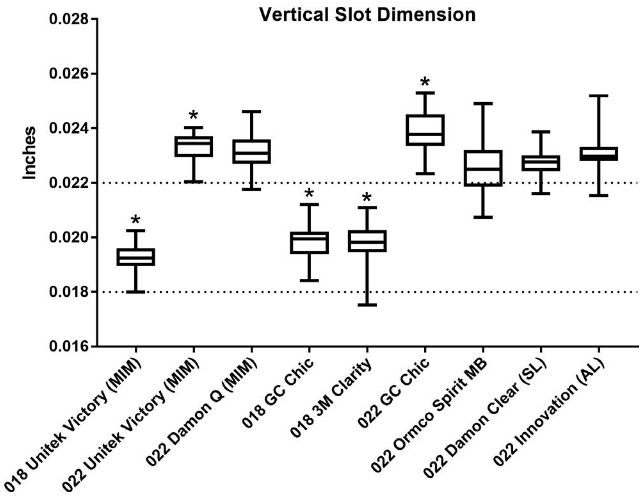

Figure 4. Graphic representation of the bracket slot dimension of the three metal and six ceramic brackets. * $P < .05$ that the bracket has a clinically relevant slot within 0.001" of its reported value.

Table 2. Comparison of Current Results to Results of the 2014 Brown et al.[1] Study for the Three Metal MIM Bracket Series They Had in Common[a,b]

	Mean Slot Measurement	SD	n	*P* Value
0.018" Unitek Victory (MIM)				
Brown et al.[1]	0.0189"	0.0003	100	<.0001*
Current study	0.0193"	0.0004	100	
0.022" Unitek Victory (MIM)				
Brown et al.[1]	0.0229"	0.0003	100	<.0001*
Current study	0.0234"	0.0004		
0.022" Damon Q (MIM)				
Brown et al.[1]	0.0229"	0.0003	78	.0194*
Current study	0.0231"	0.0007	100	

[a] MIM indicates metal injection molded; SD, standard deviation.
[b] The larger observations in the current study suggest that the difference in methods had significant consequences for the mean size of a bracket's vertical slot dimension accuracy and precision.
* Results of *t*-test for mean comparisons were significant.

the depth of the slot using a microscope with 1-μm resolution. Figure 3 shows the current method in which 40 points that form a line in the upper are measured digitally to a continuous line along the opposing slot wall. Beginning and ending at the first point of curvature, the mean average of those 40 line-to-point measurements represented the vertical slot dimension using a microscope with a 0.1-μm resolution. Though the intraclass correlation suggested high operator precision, it is estimated that most operator imprecision was due to subjective alignment of bracket slots to be exactly perpendicular to the microscope table in rope wax, as was also done in the Brown et al.[1] study.

Note that in Figure 3, in the measurements taken by Brown et al.,[1] a significant portion of the slot wall width was not accounted for when a bracket had diverging slot walls. Any averaging of the slot dimension over a linear path, as opposed to a point-to-point measurement, would render a larger slot dimension. The results in Figure 5 show that this divergence would clearly lead to brackets being oversized but would affect the 0.022" Damon Clear and 0.022" Ormco Spirit MB brackets more than the others. It was interesting that the 0.022" Ormco Spirit MB had the largest standard deviation (see Table 1) and the largest divergence (see Table 3). This was the only CIM bracket measured with a metal insert, which may present its own unique manufacturing challenges. Figure 5B illustrates qualitatively that a rectangular wire would not effectively express a given torque prescription with diverging slot walls, especially if they were already oversized.

Several investigators have reported by observation that the upper and lower walls of the slot did not always appear parallel, including Brown et al.[1] and others.[5,7] Most observations were that the walls appeared to diverge from the internal aspect to the slot mouth, which may be desired by manufacturers to avoid undercuts in the CIM/MIM molds. No published studies to date have quantified the angular relationship of the slot walls. The significant finding of diverging walls would explain the greater mean measurement values for the same bracket series observed in the Brown et al.[1] study vs the current study.

Many articles have evaluated the effect of slot play or engagement angle. Archambault et al.[7] conducted a systematic review of the engagement angle and found that the engagement angle depended on several variables, including archwire dimension, edge shape, and bracket slot dimension. They also concluded that there was much more variability and larger engagement angle values than published theoretical values. Dalstra et al.[8] measured actual torsional play in conventional and self-ligating bracket systems and found that the actual torsional play was much greater for various archwires and bracket series than anticipated from theoretical modeling. Based on the findings in this article, enabled by these new methods, it is suspected that oversized slots with nonparallel slot walls would contribute to these differences between theoretical and actual torsional play. Though this could also be explained by error in the wires, From their study of 40 different wires from five manufacturers meant for the 0.018" bracket systems, Meling et al.[9] showed that nearly all wires were within 0.5 mil of their reported values, so bracket variability within a brand and within a series are expected to be the greater source of torque play.

The main limitation in this study design, which also exists with previous methods, is that a measurement was made from a two-dimensional microscope image

Table 3. Statistics for Results in Figure 5A[a]

	0.018” Unitek Victory (MIM)	0.022” Damon Q (MIM)	0.018” GC Chic (CIM)	0.022” Damon Clear (CIM)	0.022” Ormco Spirit MB (CIM)
No. of values	39	39	36	28	32
Minimum	–0.55	–1.88	–2.1	–1.5	1.785
25% percentile	0.33	–0.12	–0.465	0.3725	3.469
Median	0.731	0.62	0.83	1.375	3.977
75% percentile	0.947	1.62	1.363	4.15	4.726
Maximum	2.11	3.39	2.38	5.55	9.119
Mean	**0.6761**	**0.7228**	**0.5956**	**1.871**	**4.404**
Standard deviation	**0.5787**	**1.27**	**1.217**	**2.154**	**1.767**
Standard error of mean	0.09266	0.2034	0.2028	0.4071	0.3123
Lower 95% CI of mean	0.4885	0.3111	0.1839	1.036	3.767
Upper 95% CI of mean	0.8637	1.135	1.007	2.706	5.041

[a] CI indicates confidence interval; CIM, ceramic injection molded; and MIM, metal injection molded.

that depended on light and correct bracket orientation. Perhaps a more comprehensive method may be developed whereby a digital three-dimensional impression of the bracket slot is captured for more accurate analysis. However, this approach becomes less practical when a high N value is required to power a study where small differences are clinically significant and would require well-designed software algorithms for analysis.

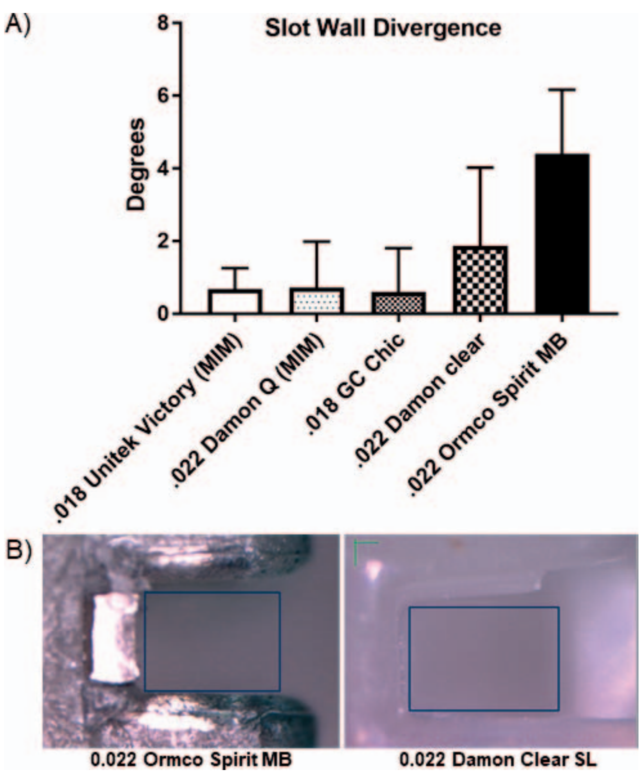

Figure 5. Bracket slot wall deviations from parallel (A) Graphic quantification of the bracket slot wall divergence of two metal injection molded metal and three ceramic injection molded brackets, measured as degrees deviation from parallel. (B) Representative images of the two most divergent brackets; rectangles are used to help visualize a true parallel slot.

A clinician expects to get full expression of the torque value as prescribed in the chosen bracket series when placing an 0.018” × 0.025” archwire in an 0.018” slot bracket series or an 0.022” × 0.028” archwire in an 0.022’’ bracket series, and this expectation was not justified by the findings of this study. In addition to the enlarged slot dimensions found, the shape of the slot may also contribute to the excessive slot play. Specifically, a bracket slot that is diverging toward the slot mouth would increase slot play or the engagement angle.

CONCLUSIONS

- A novel system for bracket slot measurement was presented that incorporates slot wall parallelism as well as the vertical dimension. The 0.018” 3M Victory (MIM) and the CIM bracket series 0.018” GC Chic, 0.022” GC Chic, and 0.018 3M Clarity did not have a bracket slot accuracy within 0.001” of their reported slot dimensions by these new methods.
- In general, these methods suggest that CIM brackets likely have a precision comparable to that of MIM brackets reported here and in prior studies, though there is variation between manufacturers.
- When orthodontic clinicians intend to express a CIM bracket’s prescription, they should expect to overcompensate for any torque not expressed due to the oversized vertical slot dimension.
- Slot parallelism is a critical contributor to vertical slot accuracy and precision.

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REFERENCES

1. Brown P, Wagner W, Choi H. Orthodontic bracket slot dimensions as measured from entire bracket series. *Angle Orthod*. 2015;85(4):678–682.
2. Profitt WR, Fields HW, Sarver DM. *Contemporary Orthodontics*. 5th ed. St Louis, MO: Mosby Elsevier; 2013.
3. Bennett JC. *Fundamentals of Bracket Selection: A User Guide*. 2nd ed. London, UK: Le Grande Publishing; 2010.
4. Cash AC, Good SA, Curtis RV, McDonald F. An evaluation of slot size in orthodontic brackets—are standards as expected? *Angle Orthod*. 2004;74:450–453.
5. Bhalla NB, Good SA, McDonald F, Sherriff M, Cash AC. Assessment of slot sizes in self-ligating brackets using electron microscopy. *Aust Orthod J*. 2010;26:38–41.
6. Nishio C, Mendes Ade M, Almeida MA, Tanaka E, Tanne K, Elias CN. Evaluation of esthetic brackets' resistance to torsional forces from the archwire. *Am J Orthod Dentofacial Orthop*. 2009;135:42–48.
7. Archambault A, Lacoursiere R, Badawi H, Major PW, Carey J, Flores-Mir C. Torque expression in stainless steel orthodontic brackets. A systematic review. *Angle Orthod*. 2010;80:201–210.
8. Dalstra M, Eriksen H, Bergamini C, Melsen B. Actual versus theoretical torsional play in conventional and self-ligating bracket systems. *J Orthod*. 2015;42:103–113.
9. Meling TR, Ødegaard J, Meling EO. Cross-sectional stability of square and rectangular stainless steel wires. *Kieferorthop Mittlg*. 1994;8:41–54.