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In This Issue:

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Letter from the Editor - David C. Sarrett, DMD, MS

Bulk-fill composites are popular restorative materials that have been on the market for several years. Unlike traditional composites, which typically are placed in maximum increments of 2 mm, bulk-fill composites are designed to be placed in 4 mm, or sometimes greater, increments. Restoring a tooth in one step certainly appears to save time, but there are some concerns. For example, manufacturers claim that bulk-fill materials have greater depth of cure and lower polymerization-induced shrinkage stress.

For this issue, the ADA Laboratory purchased 12 currently marketed bulk-fill materials and evaluated several physical and mechanical properties, comparing the products to one another and to traditional composites. This evaluation found performance of restoratives in both categories to be acceptable according to an international standard, with the exception of depth of cure and hardness. Three of the bulk-fill resin-based composites did not achieve adequate depth of cure when tested according to the standard. All products but one demonstrated adequate hardness after curing in a subsequent test (Knoop hardness test). With the exception of depth of cure and Knoop hardness, we found the laboratory performance of bulk-fill resin-based composites to be comparable to that of traditional multi-increment—fill resin-based composites.

The second article, "Evaluation of Four Dental Clinical Spectrophotometers Relative to Human Shade Observation," speaks to one of the more challenging tasks in dentistry-- selecting a shade for a restoration on a single maxillary central incisor. The correct shade of a crown has little importance in the success of the restoration, but is often the patient's foremost concern. The authors also investigated the influence of ambient lighting and evaluator's color acuity in shade selection. I hope you'll find both studies interesting and informative. Have a question or a comment? Drop me a line at ppreditor@ada.org

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Evaluation of Four Dental Clinical Spectrophotometers Relative to Human Shade Observation

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ABSTRACT

Background: Visual shade selection is often more subjective than objective. The authors conducted a clinical trial to assess the performance of four dental spectrophotometers.

Methods: Room color temperatures were recorded in degrees Kelvin. Evaluators were divided into two groups depending upon their performance on the Farnsworth Munsell – 100 Hue Test. Evaluator Group 1 (average color acuity) used the Vita Classic shade guide and four dental clinical spectrophotometers (Easyshade, Shade-X, Crystaleye, SpectroShade Micro) to determine the shade of maxillary central incisors of 367 patients. Evaluator Group 2 (superior color acuity), blinded from the previous results, visually chose a shade for the tooth assessed by the first evaluator. Patients were then asked for their opinion of all selected shades.

Results: Patients agreed with the shades chosen by the evaluators slightly more often than those determined by the spectrophotometers. When patients disagreed, they felt the chosen shades were either too light or too yellow compared to their natural tooth.

Conclusions: At best, the inter-rating reliability between spectrophotometers and evaluators was moderate. Performing well on the Farnsworth Munsell - 100 Hue test did not predict the ability to correctly choose tooth shades. Room light color temperature does affect visual shade matching for humans and spectrophotometers.

Clinical Implication: Spectrophotometers may complement, but not substitute for visual color matching methods.

Key Words: spectrophotometers, shade guides, CIE L*a*b*, delta E, Munsell, color room temperature

INTRODUCTION

One of the most challenging tasks in dentistry is selecting a shade for a restoration on a single maxillary central incisor. From a functional aspect the correct shade of a crown has little importance in the success of the restoration, but is often the foremost factor for patient acceptance. More than 80% of patients with an anterior metal ceramic restoration were aware of the shade mismatch relative to the adjacent natural tooth.[1] Restoration remakes due to shade mismatches can be a financial burden to all involved. Shade selection is normally accomplished by visually comparing the selected tooth to shade tabs from commercially available shade guides. This process is usually quick and cost effective; also, the clinician's ability to discriminate tooth color can be improved with training and experience.[2,3] However, shade selection is limited in part to the clinician's understanding of color science and is more subjective than objective. Color perception varies between persons and within persons over time.[4-7] Approximately 8% of men and 0.5% of women have a color-vision defect or difficulty differentiating reds and greens.[1] At an American Dental Association Annual Meeting, 13% of 670 participants who were screened for color vision acuity were found to have irregular color vision and 2.8% exhibited severe color vision deficiency.[8] The phenomenon of metamerism, which occurs when an object viewed under one lighting condition appears different under dissimilar lighting, occurs routinely in dentistry. Evidence exists that both supports and disproves that shade matching may also be influenced by fatigue, age, gender, experience and lighting environment.[9-15] Moreover, the range of shade tabs within shade guides does not completely cover the entire color spectrum of natural teeth.[16-20] Furthermore, there is a lack of consistency among shade tabs within the same shade guide brand.[21]

There are two systems used to describe color: the descriptive Munsell color system and the more quantitative CIELAB (Commission International de l'Eclairage) system.[22] The Munsell system describes color in three attributes: hue, chroma and value. Hue is defined as the actual color such as red, yellow, blue, etc. Chroma is the saturation or intensity of the hue while value is the degree of lightness or darkness. Used almost exclusively in color research, CIELab describes color as the product of blending three color coordinates; L*, a* and b*. The L* is the lightness ranging from white to black, a* is the redness ranging from green to red, and b* is the yellowness ranging from yellow to blue. By giving these three coordinates numerical values the CIELab system is able to locate an object in a three-dimensional color space. It can also numerically quantify the color difference (ΔE) between two objects using the following formula ΔE = the square root of $[(L_1-L_2)^2 + (a_1-a_2)^2 + (b_1-b_2)^2]$. Under controlled lighting conditions the smallest color difference detectable by the human eye is 1 ΔE. Stated in another way, a 1 ΔE is the 50:50 perceptibility threshold under controlled lighting conditions; that is 50%

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of observers will notice a difference and 50% will not. A ΔE of 2.7 and 3.3 were found to be 50:50 acceptability thresholds; that is 50% of observers will accept the restoration whereas 50% would replace the restoration because of color mismatch.[3,23]

More recently colorimeters, spectrophotometers, and image analysis techniques have been advocated to reduce the subjectivity inherent in shade selection. A colorimeter analyzes the reflected light from an object after it has been passed though red, blue and green filters. A spectrophotometer emits a white light into a spectrum of wavelength bands between 5 nm and 20 nm to illuminate the measured object. It then measures the wavelength reflected from the illuminated object. The software calculates the values for L* a* and b* and then determines the closest shade by determining the smallest ΔE value between a particular shade and the measured object. Generally, colorimeters are simpler and less expensive than spectrophotometers. A study by Dozic et al. concluded that spectrophotometers are more reliable than colorimeters.[24] Similar findings were reported by Paul et al.[25] and Kim-Pusateri and colleagues.[26] In a study in which metal ceramic crowns were fabricated by shade selection performed by a clinician using the Vitapan Classic shade guide (Vita Zahnfabrik, Bad Säckingen, Germany) or by a spectrophotometer, 9 out of 10 crowns determined to be clinically acceptable for cementation were made using the shade selected by the spectrophotometer.[25] Compared to conventional visual shade assessment, spectrophotometric analyses were determined to be more reproducible.[27-31]

The purpose of this study was to evaluate the accuracy of four commercially available dental clinical spectrophotometers in comparison with the accuracy of human evaluators. Additionally, we investigated the influence of ambient lighting and evaluator's color acuity in shade selection. We addressed four investigative questions in this study.

1) Do patients and dentists differ in the accuracy of shade selection?
2) To what extent do the instruments match the color perception of the human eye?
3) Can the Farnsworth Munsell 100 Hue Test (FM 100 Hue Test) (X-Rite Inc., Grand Rapids, MI) be used to predict evaluators' shade matching ability?
4) Do changes in ambient lighting impact shade matching?

Methods and Materials

Four dental clinical spectrophotometers were evaluated in this study: Easyshade Compact (Vita Zahnfabrik), Shade-X (X-Rite Inc., Neu-Isenburg, Germany), SpectroShade Micro (Medical High Technologies, Arbizzano di Negrar, Italy), and Crystaleye (Olympus Corp., Tokyo, Japan). This multi-centered study was completed at Virginia Commonwealth University School of Dentistry, University of the Pacific School of Dentistry and the VA Maine Healthcare—System—Togus with approval of the centers' respective institutional review boards. Prior to beginning the study, each evaluator completed the FM-100 Hue test. The test involved arranging, in order of hue, 85 color tabs of incremental hue variation spanning the visible spectrum. Testing was conducted in the same rooms that patient evaluations took place. Total error scores were calculated using scoring software. The results were used to separate evaluators with normal color vision into classes of superior and average color acuity.[32] Evaluators with the fewest errors on the FM-100 Hue Test were designated as "Evaluator 2 or superior color acuity" all others were designated "Evaluator 1 or average color acuity." Virginia Commonwealth University School of Dentistry had seven individuals designated as Evaluator 1 and three designated as Evaluator 2, University of the Pacific School of Dentistry had 12 designated as Evaluator 1 and two as Evaluator 2. The Veterans Administration had one designated as Evaluator 1 and one as Evaluator 2. Ambient room light color temperature was measured using Prodgi Color C-500 camera (Sekonic, North White Plains, NY) from the position of the dental chair facing each cardinal direction and the ceiling. Each measurement (recorded in degrees Kelvin) was repeated five times to maximize validity. Patients (n=367) enrolled in the study were between the ages of 18 and 99, provided informed consent, possessed a vital maxillary central incisor free of plaque and restorations. If lipstick was present, it was removed. Patients were excluded from the study if they had tooth whitening or bleaching within the past 24 months, had discolored gingival tissues, recession or severe gingivitis. Additionally, patients were excluded if the shade of the tooth appeared to be obviously outside the range of the Vitapan Classic Shade Guide.

For each patient, Evaluator 1 visually determined a shade for the middle third of a selected maxillary central incisor by comparing it to shade tabs from the Vitapan Classic Shade Guide. Following the manufacturers' instructions, Evaluator 1 calibrated each dental clinical spectrophotometer and recorded the shade of the middle third of the selected maxillary central incisor. Subsequently, and blinded from the results obtained from Evaluator 1 and spectrophotometers, Evaluator 2 selected a shade by visual evaluation using the Vitapan Classic Shade guide. Conceivably, each subject could have six different shades chosen for the same tooth: a different shade from each of the four spectrophotometers and one each from the two evaluators. In the final phase of the evaluation, the patient was handed a mirror and each of the selected shade tabs and asked "do you agree this is an adequate representation of your tooth shade?" Theoretically, the patient could agree or disagree with multiple selected shades.

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For each shade tab the patient disagreed with they were asked "what is the primary reason the selected shade does not match?" According to the protocol, the patient could select one of the following six options: too light, too dark, too brown, not brown enough, too yellow, not yellow enough.

RESULTS

Inter-rater Agreement

Table 1 illustrates the percentage of agreement of the selected shades among the two evaluators, four dental clinical spectrophotometers and patient. The greatest agreements were between patients and group 1 evaluators (43.8%) and patients and group 2 evaluators (55.7%). Evaluators 1 and 2 agreed with each other 41% of the time. The group 2 evaluators' assessments agreed with those of both Crystaleye and Spectroshade Micro at a rate of 35.6 percent.

Table 1. Percentage agreement between evaluators, spectrophotometers and patients.

	Evaluator 1	Evaluator 2
Evaluator 1	n/a	41.0%
Evaluator 2	41.0%	n/a
SpectroShade Micro	42.9%	35.6%
Crystaleye	36.2%	35.6%
Shade-X	34.3%	28.5%
Easyshade	30.7%	30.7%
Patient	43.8%	55.7%

Dental clinical spectrophotometers agreed more consistently with the findings of group 1 evaluators than with the findings of group 2 evaluators, except for Vita Easyshade Compact, which showed the same rate of agreement with the findings of both group 1 and group 2 evaluators. Vita Easyshade Compact and Shade-X had the lowest agreement percentages with evaluators. Inter-rater reliability was calculated by an ADA statistician according to the interpretation guidelines suggested by Landis and Koch, in which a value of 1 represents perfect agreement and a value of 0 poor agreement.[33] (See Table 2)

A higher number reflects better inter-rater reliability. In Table 2 yellow boxes denote moderate agreement, orange fair and red slight agreement. All possible comparisons showed significantly greater agreement than would be expected due to random chance ($p < 0.001$). The comparison between Crystaleye and SpectroShade Micro had the highest inter-rating reliability (0.4622), whereas group 2 evaluators and Shade-X had the lowest (0.1434). SpectroShade Micro demonstrated best overall match with those of other evaluators and instruments.

Quantifying Disagreement

For those evaluations for which the shades selected by any two methods (dental clinical spectrophotometer or human) did not agree, color differences (ΔE) were calculated. The L*a*b* values of each Vitapan Classic Shade Tab were measured by the ADA Laboratories. (See Table 3 on page 5).

This made it possible to quantify the disagreement between shade choices, instead of simply determining that there was disagreement. The box plot (Figure 1 on page 5) displays the range and means of ΔEs between each pair of evaluators and instruments. Larger ΔE values are due to greater shade disagreements; likewise smaller ΔEs reflect less disparity.

None of the means significantly differ from each other, meaning each dental clinical spectrophotometer or evaluator disagreed to the same extent. To help conceptualize the significance to which the evaluators disagreed, the average ΔE was 3.29 or about 2.5 times the smallest ΔE possible between any two Vitapan Classic shades (ΔE between C2 and D4 is 1.35). (See Table 3 on page 5)

Table 2. Inter-rater reliability.

	Fleiss's Generalized Kappa					
	Evaluator 1	SpectroShade Micro	Crystaleye	Shade-X	Easyshade	Evaluator 2
Evaluator1	--	0.3119	0.2181	0.1957	0.1664	0.2821
SpectroShade Micro	0.3119	--	0.4662	0.3084	0.2163	0.2182
Crystaleye	0.2181	0.4662	--	0.2865	0.1786	0.2090
Shade-X	0.1957	0.3084	0.2865	--	0.2049	0.1434
Easyshade	0.1664	0.2163	0.1786	0.2049	--	0.1735
Evaluator 2	0.2821	0.2182	0.2090	0.1434	0.1735	--

Value of 1 is perfect agreement, value of 0 is poor agreement. Yellow boxes denote moderate agreement, orange fair and red slight agreement.

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Table 3. L*a* b* values of Vita Classic Shade tabs

= Square Root ((L1-l2)2 + (a1-a2)2 +(b1-b2)2)1/2																			
VITA CLASSIC SHADE GUIDE			L	66.33	64.43	61.65	59.07	56.73	64.84	65.53	61.37	60.37	62.71	60.1	57.62	54.96	61.26	59.43	59.32
			a	0.3	1.46	1.71	2.65	3.02	-0.23	0.28	1.84	1.98	0.42	1.21	1.54	2.35	0.55	1.61	0.76
			b	8.73	11.18	12.2	14.6	14.2	7.64	11.45	14.96	15.89	8.86	11.86	12.15	12.84	7.5	10.2	12.87
L	a	b	shade	A1	A2	A3	A35	A4	B1	B2	B3	B4	C1	C2	C3	C4	D2	D3	D4
66.33	0.3	8.73	A1		3.31	5.99	9.63	11.38	1.92	2.84	8.11	9.47	3.62	7.03	9.44	12.20	5.22	7.18	8.15
64.43	1.46	11.18	A2	3.31		2.97	6.47	8.42	3.94	1.64	4.88	6.24	3.07	4.39	6.88	9.62	4.94	5.10	5.43
61.65	1.71	12.2	A3	5.99	2.97		3.65	5.47	5.89	4.20	2.78	3.92	3.73	1.66	4.03	6.73	4.86	2.99	2.60
59.07	2.65	14.6	A35	9.63	6.47	3.65		2.40	9.49	7.57	2.46	1.95	7.15	3.26	3.06	4.56	7.72	4.54	2.57
56.73	3.02	14.2	A4	11.38	8.42	5.47	2.40		10.93	9.62	4.85	4.15	8.43	4.48	2.68	2.45	8.46	5.03	3.69
64.84	-0.23	7.64	B1	1.92	3.94	5.89	9.49	10.93		3.91	8.36	9.64	2.54	6.51	8.69	11.37	3.67	6.26	7.67
65.53	0.28	11.45	B2	2.84	1.64	4.20	7.57	9.62	3.91		5.66	7.02	3.83	5.52	8.04	10.84	5.82	6.37	6.39
61.37	1.84	14.96	B3	8.11	4.88	2.78	2.46	4.85	8.36	5.66		1.37	6.40	3.41	4.70	6.84	7.57	5.15	3.12
60.37	1.98	15.89	B4	9.47	6.24	3.92	1.95	4.15	9.64	7.02	1.37		7.57	4.11	4.66	6.32	8.56	5.78	3.42
62.71	0.42	8.86	C1	3.62	3.07	3.73	7.15	8.43	2.54	3.83	6.40	7.57		4.05	6.16	8.84	1.99	3.74	5.26
60.1	1.21	11.86	C2	7.03	4.39	1.66	3.26	4.48	6.51	5.52	3.41	4.11	4.05		2.52	5.32	4.56	1.83	1.35
57.62	1.54	12.15	C3	9.44	6.88	4.03	3.06	2.68	8.69	8.04	4.70	4.66	6.16	2.52		2.82	5.99	2.66	2.00
54.96	2.35	12.64	C4	12.20	9.62	6.73	4.56	2.45	11.37	10.84	6.84	6.32	8.84	5.32	2.82		8.33	5.15	4.65
61.26	0.55	7.5	D2	5.22	4.94	4.86	7.72	8.46	3.67	5.82	7.57	8.56	1.99	4.56	5.99	8.33		3.43	5.71
59.43	1.61	10.2	D3	7.18	5.10	2.99	4.54	5.03	6.26	6.37	5.15	5.78	3.74	1.83	2.66	5.15	3.43		2.80
59.32	0.76	12.87	D4	8.15	5.43	2.60	2.57	3.69	7.67	6.39	3.12	3.42	5.26	1.35	2.00	4.65	5.71	2.80	
			max	12.20	9.62	6.73	9.63	11.38	11.37	10.84	8.36	9.64	8.84	7.03	9.44	12.20	8.56	7.18	8.15
			min	1.92	1.64	1.66	1.95	2.40	1.92	1.64	1.37	1.37	1.99	1.35	2.00	2.45	1.99	1.83	1.35

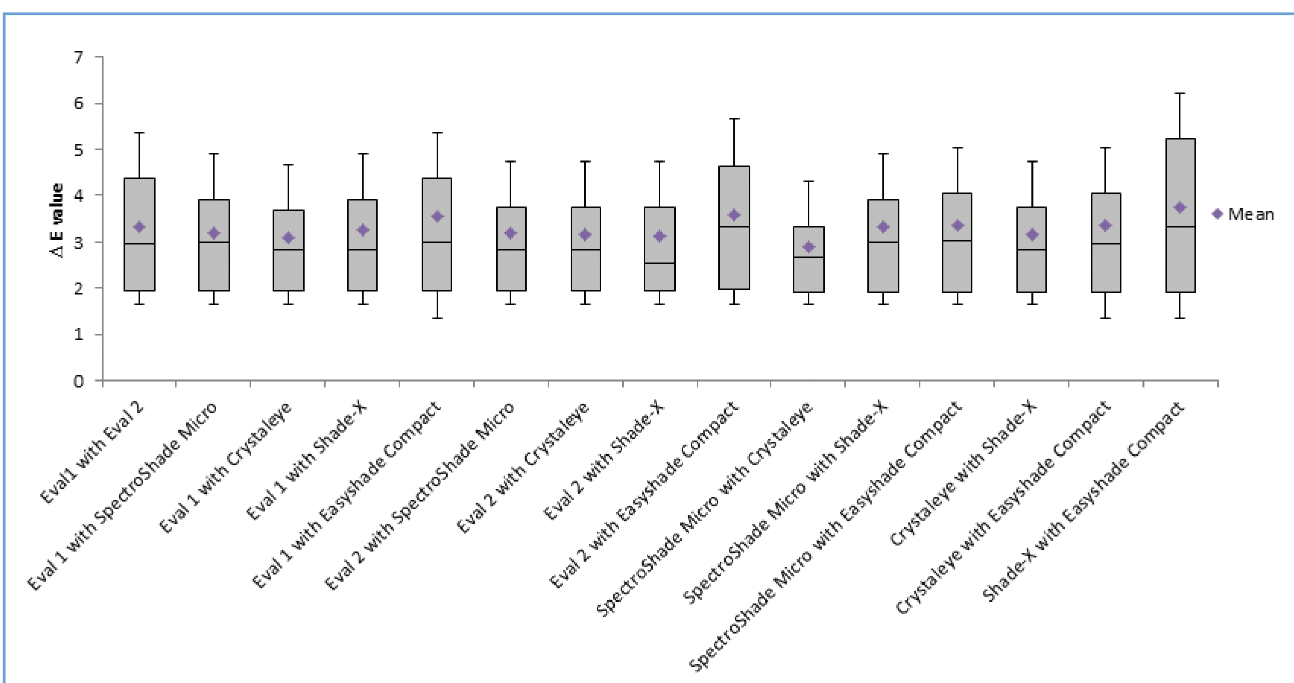

Figure 1. Mean ΔE between evaluators and spectrophotometers.

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Table 4. Farnsworth Munsell -100 Hue Test scores and matching percentage of Evaluator #1

Code	% Total Matching	Munsell score
1	36.1%	24
3	12.5%	32
4	39.7%	72
5	39.0%	56
7	30.00%	20
8	36.6%	32
9	60.4%	24
11	16.7%	32
12	50.0%	48
13	33.3%	36
14	20.0%	44
15	33.3%	56
16	0.00%	44
17	20.8%	12
18	34.8%	28
19	43.9%	48
20	19.4%	128
21	0.00%	20
22	50.00%	68
23	5.6%	120
24	42.6%	32
25	25.00%	40
26	50.00%	44
27	60.00%	96
28	28.6%	28
29	29.2%	76

Lower FM – 100 scores correspond to better performance on the test.

Table 5. Farnsworth Munsell - 100 Hue Test scores and matching percentage of Evaluator #2

Code	% Total Matching	Munsell score
1	33.8%	24
2	34.7%	16
6	39.7%	8
9	0.00%	24
10	35.2%	16
11	46.2%	20
12	66.7%	36
13	39.4%	12
14	38.0%	16
15	0.00%	44
16	43.6%	12

Lower FM – 100 scores correspond to better performance on the test.

Farnsworth Munsell - 100 Hue Test

Tables 4 and 5 illustrate the FM-100 Hue Test scores of each evaluator and their total matching percentage between the four instruments, patient and the other evaluator. For example, in Table 4 (Evaluator 1 or average color acuity), the individual identified as 4 had a FM-100 Hue Test score of 72 and a match percentage of 39.7%.

Similarly, in Table 5 (Evaluator 2 or superior color acuity) the individual identified as 6 had the best FM-100 Hue Test score of 8 and a total matching percentage of 39.7%. An individual with average color acuity performed as well as the evaluator with superior color acuity. Single variable regression models were used to determine the significance of the FM-100 Hue Test on shade selection by the evaluators.

Table 6. Maximun likelihood estimate

	Evaluator 1	Evaluator 2
Evaluator 1	n/a	0.3488
Evaluator 2	0.7377	n/a
SpectroShade Micro	0.6026	0.1273
Crystaleye	0.0594	0.1845
Shade-X	0.5217	0.0114
Easyshade	0.5912	0.0221
Patient	0.0463	0.2722

P value less than 0.05 means the evaluator's FM - 100 test score predicts the degree of agreement.

Table 6 shows p values of how well the FM-100 Hue Test scores of the collective individuals fit the data. A p value less than 0.05 (highlighted in yellow) indicates the evaluator's FM-100 Hue Test score significantly predicts agreement between the instruments, patient and other evaluator.

Table 7. Maximun likelihood estimate

	Evaluator 1	Evaluator 2
Evaluator 1	n/a	0.026
Evaluator 2	-0.002	n/a
SpectroShade Micro	-0.003	-0.042
Crystaleye	-0.010	-0.037
Shade-X	0.004	-0.075
Easyshade	-0.003	-0.067
Patient	0.011	-0.031

The larger the absolute value, the more impact the FM – 100 test score has on shade matching.

Table 7 illustrates the maximum likelihood estimate parameter for each paring.

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The larger the absolute value, the more impact the FM-100 Hue Test predicts shade matching. These two regression models were used to calculate the odds that the evaluator would not match the shade selected by the instrument or patient.

An odds ratio (Table 8) is significant if the 95% confidence interval does not contain 1 (highlighted in yellow).

Table 8. Odds Ratio (95% Confidence Interval)

	Evaluator 1	Evaluator 2
Evaluator 1	n/a	1.027 (0.972, 1.085)
Evaluator 2	0.998 (0.988, 1.009)	n/a
SpectroShade Micro	0.997 (0.987, 1.008)	0.958 (0.907, 1.012)
Crystaleye	0.99 (0.979, 1.000)	0.963 (0.912, 1.018)
Shade-X	1.004 (0.992, 1.015)	0.928 (0.876, 0.983)
Easyshade	0.997 (0.986, 1.008)	0.935 (0.883, 0.990)
Patient	1.011 (1.000, 1.023)	0.970 (0.918, 1.024)

Odds ratio is considered significant if the 95% confidence interval does not contain 1. Evaluators' FM -100 test scores were not significant predictors of shade matching.

These regression models indicate that, for the majority of comparisons, evaluators' FM-100 Hue Test scores were not significant predictors of the ability to correctly select shades. There were three exceptions. The degree of matching between Evaluator 1 (average color acuity) and patients decreased as Evaluator 1's FM-100 Hue Test scores increased. The opposite relationship is seen between Evaluator 2 (superior color acuity) and Easyshade and between Evaluator 2 and Shade-X; shade matching increased as the evaluators' FM-100 Hue Test score increased.

Figure 2 is a scatter plot of individual evaluators with their overall matching percentage as the Y-axis and their FM-100 Hue test scores as the X-axis. Individuals designated Evaluator 1 are identified in blue while those designated Evaluator 2 are red. All evaluations were used to create a single linear regression line with blue shading above and below indicating the 95% confidence interval of matching percentage. If for instance the line had a significant negative slope (lower FM-100 Hue Test scores and higher matching percentage at the right end of the graph and higher FM-100 Hue Test scores with lower matching percentage at the right end of the graph) it would support the hypothesis that a lower FM-100 Hue Test score (better color acuity) is associated with higher shade matching ability. However, the slope of the line is nearly zero (slope = -0.043). Therefore, FM-100 Hue Test scores were weak predictors of an evaluator's shade matching ability.

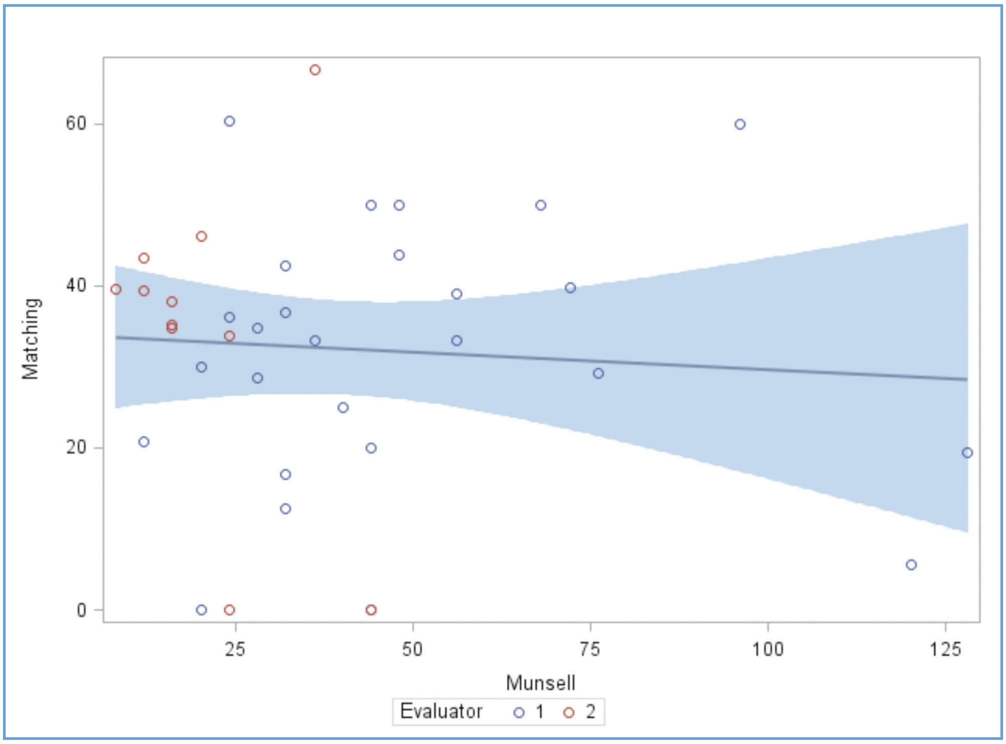

Figure 2. Evaluator Matching by Munsell Score. Farnsworth Munsell – 100 Hue Test and shade matching percentage of evaluators.

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Table 9. Patient Agreement with Evaluation

	1st eval	SpectroShade Micro	Crystaleye	Shade-X	Easyshade	2nd eval
Aagree	44%	42%	39%	36%	35%	57%
Too Light	50%	38%	42%	48%	38%	43%
Too Dark	13%	19%	22%	15%	22%	18%
Too Brown	6%	8%	6%	8%	5%	7%
Not Brown Enough	1%	1%	2%	2%	1%	1%
Too Yellow	29%	31%	26%	27%	32%	29%
Not Yellow Enough	1%	1%	1%	0%	2%	2%
Total	100%	100%	100%	100%	100%	100%

Percentage of patients that agreed with the selected shade and why they disagreed.

Table 10. Maximum Likelihood Estimate for Room Lighting Color Temperature

	Evaluator 1	Evaluator 2	SpectroShade Micro	Crystaleye	Shade-X	Easyshade
Evaluator 1	n/a					
Evaluator 2	-0.02	n/a				
SpectroShade Micro	-0.24	-0.12	n/a			
Crystaleye	-0.50	-0.69	-0.18	n/a		
Shade-X	-0.31	-0.19	-0.72	-0.33	n/a	
Easyshade	-0.46	-0.42	-0.32	-0.54	-0.14	n/a
Patient	0.77	0.41	0.75	0.54	0.70	0.32

The larger the absolute value the greater the impact on shade matching. Higher values are shaded in yellow.

Patient Agreement

The percentage of shade agreements between patients and those shades chosen by the evaluators and dental clinical spectrophotometers are shown in Table 9.

From this simple comparison patients agreed with evaluators and instruments between 35% (Easyshade) to 57% (Evaluator 2) of the time. Homogeneity was tested and rejected which indicated at least one of the values is significantly different from the others. Marascuillo procedure was used for simultaneous comparisons and indicated Evaluator 2 had statistically higher agreement with patients than with the four spectrophotometers or Evaluator 1. Generally speaking, if patients disagreed they thought the chosen shades were too light (38% to 50%) or too yellow (26% to 32%). (See Table 9)

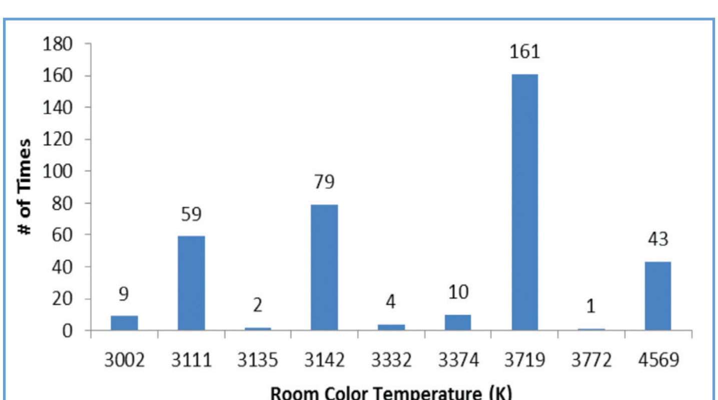

Figure 3. Room Lighting Color Temperatures

Influence of Room Lighting Color Temperature

Figure 3 illustrates the room lighting color temperature (measured in degrees Kelvin) and the number of evaluations completed in each of the nine rooms used.

Due to several low sample sizes, rooms were grouped and categorized as "low" temperature (below 3200°K) and "high" temperature (above 3700°K). Logistic regression models were used to predict matching between evaluators, instruments and patients. Table 10 shows the maximum likelihood estimate or the magnitude of the effect of room lighting color temperature has on shade matching. The larger the absolute value of the estimate, the greater the impact of room lighting color has on matching. High absolute values are shadowed in yellow. Negative estimates (such as – 0.50 between Evaluator 1 and Crystaleye) indicate that as the room lighting color temperature increased, matching increased.

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Table 11. Maximum likelihood estimate *P* values

	Evaluator 1	Evaluator 2	SpectroShade Micro	Crystaleye	Shade-X	Easyshade
Evaluator 1	n/a					
Evaluator 2	0.921	n/a				
SpectroShade Micro	0.271	0.582	n/a			
Crystaleye	0.031	0.003	0.410	n/a		
Shade-X	0.181	0.435	0.002	0.138	n/a	
Easyshade	0.054	0.082	0.158	0.023	0.551	n/a
Patient	0.001	0.059	0.001	0.016	0.002	0.156

Statistically significant p values are shaded in yellow.

Positive estimates (such as 0.77 between Evaluator 1 and patients) mean that as the room lighting color temperature increased, matching decreased. Those that are statistically significant are highlighted in yellow ($p<0.05$). (See Table 11)

Inter-evaluator agreement, inter-device agreement, and agreement between evaluators and dental clinical spectrophotometers were noted with higher room lighting color temperatures. However, only the following pairs attainted statistical significance: Crystaleye – Evaluator 1; Crystaleye – Evaluator 2, Shade-X – SpectroShade Micro and Crystaleye – Easyshade. Patients agreed with evaluators and instruments more often at low temperatures than at high lighting color temperatures. Statistical significance was only attained for comparisons between patients and Evaluator 1, and between patients and the instruments (except for Easyshade). Overall, the probability of matching was increased at high room lighting color temperature than at low room temperatures.

DISCUSSION

Inter-rater Agreement

In this study Evaluator 1 and 2 agreed 41% of the time which is close to the findings of Hugo et al. who reported 40.2% agreement among three examiners.[34] This may seem discouraging, but it is better than results reported by Paul et al.[28] In their study three experienced clinicians selected the same shade of a central incisor only 26.6% of the time. In the same study visual and spectrophotometric shade selections matched 63% of the time whereas in this study the best percentage match was 42.9% (Evaluator 1 and Spectroshade Micro). Dancy and colleagues found no difference in shade selection using conventional visual measurement by two experienced clinicians or using spectrophotometric analysis of photographs.[35] Kim-Pusateri reported high reliability for spectrophotometers, that is the ability to make consistent repeated measurements, but significant differences in accuracy or the ability to choose the correct shade.[26] Khashayar et al. found that the L*a*b* values measured from two different spectrophotometers of the same tooth were not comparable. However, if the output is given as a shade, then they match each other better because the instruments select the closest shade match from their internal shade database.[36] We detected even better agreement between patient and Evaluator 1 (43.8%) and between patient and Evaluator 2 (55.7%), which is significant since the goal is to have a patient who accepts the selected shade and ultimately the final restoration.

We found the best agreement between Crystaleye and SpectroShade Micro (Fleiss's Generalized Kappa – 0.4662), and the least between VITA Easyshade Compact and Crystaleye (Fleiss's Generalized Kappa – 0.1786) As Crystaleye and Spectroshade Micro share a similar principle of complete tooth surface measurement (CTSM), one would expect reasonable agreement between them However, these dental clinical spectrophotometers "average out" color data over the complete tooth surface or larger defined areas, which may generate measurement inaccuracies.[37] Easyshade and Shade-X follow the limited area measurement (LAM) principle; the reduced window size may cause loss of light along the edge of the object due to tooth translucency.[38] Those differences in operating principles between LAM and CTSM spectrophotometers would explain, at least in part, such disagreement, as we observed in this study. Poor inter-device agreement between CTSM and LAM dental clinical spectrophotometers is well documented.[34,36,39-41]

Inter-device agreement may also be influenced by variations in tooth surface texture and luster, convexity, enamel translucency, layering effect of enamel on dentin and positioning errors.[26,39-43] However, inter-device agreement improves with operator training.[39] The mixed level of operator training may explain why some studies reported acceptable to excellent agreement between examiners using dental clinical spectrophotometers while other researchers indicated poor agreement.[27,43-45]

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Clinically Acceptable ΔE

There isn't a universally accepted agreement for a ΔE threshold that is clinically acceptable. Clinically acceptable differences (ΔE) reported in the literature were 2.6,[46] 3.3,[47] and 3.7.[48] The US Public Health Service determined that a ΔE value of 3.7 was the upper threshold of being clinically acceptable[49] In this study the average ΔE was 3.9, which was slightly greater than what is considered clinically acceptable. The lowest ΔEs were less than 2 and the highest was 6. (Figure 1)

What a clinician and patient perceive as a color differences and what they approve as clinically acceptable may be very different. Perceptibility thresholds may not be important if the acceptability thresholds are significantly higher.[50]

Farnsworth Munsell - 100 Hue Test

It was hypothesized that evaluators who performed well on the FM-100 Hue Test would have a higher percentage of shade matches. However, the results indicated that the FM-100 Hue test was a weak predictor of shade matching ability. It is probable for an individual to lack color discrimination in hues outside those of natural teeth (red and blue), receive a poor score on the FM-100 Hue Test, but accurately discriminate the yellow hues and natural tooth shades. Clinicians with impaired hue discrimination may rely more on value assessment to select shades. A study by Alomari and Chadwick support the findings that the FM-100 Hue Test score is a weak predictor of dental shade matching performance.[32] A simpler and readily available in-office test for assessing color acuity is to match shade tabs of two Vitapan Classic shade guides.[51]

Shade Guides

Our findings suggest that the most important aspect in shade selection is value determination. Generally speaking, when patients disagreed with a selected shade, they thought it was too light or too yellow. (See Table 9) The Vita 3D Master Shade Guide, (Vident, Brea, California) is designed to help the evaluator assess the value first, then saturation and lastly to hue. The superiority of this guide over the Vita Classical Shade Guide is well documented.[52-55] Additionally, many clinicians arrange shade tabs of Vita Classical Shade Guide by value rather than hue. Recognizing the critical impact of value determination[56] some authorities recommend selecting the value first, then hue and lastly chroma.[57] That being said, one would expect the FM-100 hue test score to be only a weak predictor of shade matching performance. The difference in hue is less apparent as we move up on the value scale in the Munsell color system. However, as value decreases, hue and saturation become more distinct, and good hue discrimination ability may be useful as confounding factors (evaluator bias, fatigue, age, sex, experience, lighting environment) are reduced.

The Vitapan Classic Shade Guide was created by a complete denture lab technician in 1956 to what he thought denture teeth should look like. It has not changed in 57 years. The shade tabs are not systematically distributed in the color space related to human teeth.[58-60] The shade guide is arranged by hues that are identified by letters (A – reddish brown), (B – reddish yellow), (C – gray) and (D – reddish gray). The calibration in value and chroma (1 through 4) are not uniform. Some shades may be more difficult to match than others, with the C shades least likely to be matched.[11] There are differences among several shade tabs small enough to make them almost indistinguishable by the human eye (See Table 3). For example, the ΔE between B4/B3 is 1.37, between D4/C2 is 1.35 and between B2/A2 is 1.6 Despite these flaws the Vita Classic guide is the most commonly used commercial shade guide.[25]

In 1998, Vita 3D-Master shade guide was introduced as an improvement to the Vitapan Classic shade guide. It is purported to cover virtually all naturally occurring tooth shades. The concept of the 3D-Master system is based on a color classification principle where value, chroma and hue have been positioned an equal distance from each other. Therefore, the shade determination can be systematically determined. Vitapan 3D-Master Shade Guide was associated with significantly better intra-rater reliability among general dentists than the Vitapan Classic, but not among prosthodontists.[61] Coverage error describes the mean color difference between each evaluated natural tooth and the best matching shade tab from a given shade guide. Vitapan 3D-Master shade guide system has the smallest coverage errors (2.7ΔE to 3.93 ΔE)[60,62] when compared to the Vita Classic (3.02ΔE to 5.39 ΔE.).[58,60] Shade guides with smaller coverage error are superior to those with larger coverage error. Unfortunately, this study could not use the 3D-Master Shade Guide because several of the dental clinical spectrophotometers are able to record intermediate shades for the 3D-Master Shade Guide while some evaluators may not be able to discriminate at that level.

Room Lighting Color Temperature

It was hypothesized that room lighting color temperature would have an effect on shade selection by evaluators and patients, but would not affect spectrophotometers. The results of this study did not support this hypothesis. After applying a plastic infection control cover, Easyshade and Shade-X are positioned directly on the tooth surface. Crystaleye and SpectroShade Micro have black infection control contact caps that are designed to prevent ambient room light from interfering with the shade capturing process. Additionally, all four spectrophotometers contain their own light source for standardized illumination and therefore should be able to eliminate inconsistencies in room lighting color temperature.

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Dental clinical spectrophotometers may be affected by the amount of light reflected back into the instrument from the target surface. Therefore, positioning the probe or mouthpiece in the correct orientation is essential to mitigate improper light reflection from the tooth's surface. Other authors have recommended that shade determination occur in rooms with a lighting temperature between 5500°K and 6500°K.[1,63,64] Due to facility limitations a majority of the evaluations occurred below 4000°K. Our data shows that the probability of matching shades increased with higher room lighting color temperatures and decreased with lower temperatures. Therefore, one can postulate that the matching percentage could be improved if the room lighting temperatures were closer to the recommended temperatures of 5500°K to 6500°K. Sarafianou and colleagues have demonstrated the influence of room illumination on dental clinical spectrophotometers and confirmed that the repeatability of Easyshade and Spectroshade Micro under natural light, dental unit lamp and daylight lamp was not satisfactory for clinical practice.[39] Consistency of artificial lightening may be more important than the type of lighting.

Light physics considers three variables in determining color: 1) light source(s), which illuminate(s) the object; 2) object – reflects, absorbs, transmits the incident light, and 3) observer (human eye, instrument): perceives, processes and interprets the reflected light. Direct contact on tooth surfaces (LAM spectrophotometers) does not completely seal the device from ambient light. Since tooth surfaces are generally convex not flat, the influence of external light entering the periphery of LAM dental clinical spectrophotometers cannot be completely eliminated. The black infection control caps (CTSM instruments) cannot fully negate some "seepage" of ambient light, unless they are custom made to fit perfectly on the arch, which is clinically impractical.

Study Limitations

This study had several limitations. First, not all evaluators performed the same number of evaluations. Some completed only a few, while other clinicians completed nearly 100. Second, each evaluator and patient used their own process for visually determining shade. We did not require that evaluators and patients use a standard process for shade determination. Additionally, to maximize the reliability of each spectrophotometer, multiple recordings should have been documented for each patient. Finally, evaluators and patients used multiple Vita Classical Shade Guides. King and deRijk demonstrated variations in the L* a* b* values among Vita Classical Shade Guides to be of such clinical importance that shade guides of the same brand should not be considered interchangeable.[21]

CONCLUSIONS

Human evaluators had slight to fair agreement with the shades selected by the dental clinical spectrophotometers.

There is not a significant association between color acuity (lower scores on FM-100 Hue test) and shade matching ability.

Patients agreed 44% of the time with Evaluator 1 or those having average color acuity. They agreed significantly more often with Evaluator 2 (56%), or those having superior color acuity, than with Evaluator 1 or any of the dental clinical spectrophotometers tested.

Ambient lighting or room color temperature has a statistically significant impact on shade matching.

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A Laboratory Evaluation of Bulk-Fill Versus Traditional Multi-Increment-Fill Resin-Based Composites

Amer Tiba, PhD; Gregory G. Zeller, DDS, MS; Cameron Estrich, MPH; Albert Hong

Unlike traditional composites, which typically are placed in maximum increments of 2 millimeters (mm), bulk-fill composites are designed to be placed in 4 mm, or sometimes greater, increments.

Some concerns exist, however, regarding bulk-fill composites. One proposed rationale for limiting composite increments to 2 mm is to allow the curing light to penetrate to the resin farthest away from the light source.[1,2] A second reason for using 2-mm increments is to minimize the shrinkage and shrinkage-induced stress associated with composite polymerization. Contraction stresses that exceed the adhesive strength of the composite may result in gaps between composite and cavity walls.[3-5] It is widely believed that these marginal gaps may lead to microleakage, sensitivity and secondary caries,[1,6-11] although there is little clinical evidence to support that secondary caries are caused by this gap formation.[3,12]

Manufacturers claim that bulk-fill materials have greater depth of cure and lower polymerization-induced shrinkage stress thanks to technology like "polymerization modulators," which they say allow a certain amount of flexibility and optimized network structure during polymerization.[13]

Studies have demonstrated some comparable physical and mechanical properties among a handful of bulk-fill and traditional composites.[9,14,15]

This study evaluates more in-depth physical and mechanical properties of currently marketed bulk-fill materials in comparison to one another and to traditional composites.

For this evaluation, the ADA Laboratory purchased and evaluated 12 composite resins listed in Table 1.

Table 1. Evaluated Incremental and Bulk-Fill Composites.

Product Manufacturer	Recommended Placement Method	Evaluated Shade
Traditional Universal Composites		
Filtek Supreme Ultra Universal Restorative 3M ESPE 800-634-2249 www.3MESPE.com	Increments	A2
Heliomolar HB Ivoclar Vivadent 800-533-6826 www.ivoclarvivadent.com	Increments	A2
High Viscosity Composites		
Alert Condensable Composite Pentron 877-677-8844 www.pentron.com	Bulk	A2
HYPERFIL Parkell, Inc. 800-243-7446 www.parkell.com	Increments or Bulk	Universal
QuiXX Posterior Restorative Dentsply Caulk 302-422-4511 www.dentsply.com	Bulk	Universal
SonicFill Kerr 800-Kerr-123 www.kerrdental.com/sonicfill	Bulk	A2
Tetric EvoCeram Bulk Fill Ivoclar Vivadent 800-533-6825 www.ivoclarvivadent.us.com	Bulk	IV A
x-tra fill VOCO 888-658-2584 www.vocoamerica.com	Bulk	Universal
Flowable Composites		
Filtek Bulk Fill Flowable Restorative 3M ESPE 800-634-2249 www.3MESPE.com	Bulk	A2
SureFil SDR flow Dentsply Caulk 302-422-4511 www.surefilsdrflow.com	Bulk	A2
Venus Bulk Fill Heraeus 800-431-1785 www.heraeus-dental.com	Bulk	Universal
x-tra base VOCO 888-658-2584 www.vocoamerica.com	Bulk	A2

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SUMMARY OF TESTS

Depth of Cure and Knoop Hardness Tests

Clinical significance: These tests provide an indication of the total depth to which the composite will cure or the surface hardness you will achieve when the composite is irradiated by a curing light for the amount of time recommended by the manufacturer.

Methods: We measured the depth of cure for a cylindrical sample of 11 composites according to the standard test method (ISO 4049-2009).[16] We also recorded a relative bottom-to-top hardness measurement based on the Knoop hardness test of each specimen, to assess the degree of conversion after light curing.[1,17,18] We measured depth of cure for all of the composites except HYPERFIL, which is a dual-cure material; according to ISO 4049-2009,[16] the depth of cure test is not applicable to dual-cure materials.

To test the depth of cure, we prepared specimens of each composite (except HYPERFIL) according to the manufacturer's instructions, using the Optilux 501(Kerr) polymerization unit with a light power density of >600mW/cm². We prepared cylindrical specimens according to ISO 4049-2009 and measured the height of a cured specimen with a micrometer (±0.1mm).[16]

Table 2. Mean Depth of Cure (DOC, n=3)and Mean Bottom:Top Knoop Hardness Ratio (n=5) for Incremental vs. Bulk-Fill Composites.

Product Manufacturer (Recommended placement method)	Mfr. Claimed DOC (mm)	Mean±SD Tested DOC* (mm)	Mean±SD Bottom: Top Knoop Hardness Ratio*‡ (%)
Traditional Universal Composites			
Filtek Supreme Ultra Universal Restorative 3M ESPE (Incremental)	2	2.63±0.03 g	100±2 i
Heliomolar HB Ivoclar Vivadent, Inc. (Incremental)	2	1.8±0.00 h	82±2 j
High Viscosity Composites			
Alert Condensable Composite Pentron (Bulk)	5	2.53±0.06 g	35±2 k
HYPERFIL Parkell, Inc. (Dual cure: incremental or bulk)	Unlimited	NA†	87±1 l
QuiXX Posterior Restorative Dentsply (Bulk)	4	5.16±0.16 a	89±2 l
SonicFill Kerr (Bulk)	5	3.67±0.03 e	98±1 i,m,n
Tetric EvoCeram Bulk Fill Ivoclar Vivadent, Inc. (Bulk)	4	3.32±0.10 f	81±1 j
x-tra fill VOCO (Bulk)	4	4.25±0.11 c,d	98±1 i,n
Flowable Composites			
Filtek Bulk Fill Flowable Restorative 3M ESPE (Bulk)	4	3.86±0.01 e	94±1 o
SureFil SDR flow Dentsply Caulk (Bulk)	4	4.17±0.03 d	89±2 l
Venus Bulk Fill Heraeus (Bulk)	4	4.87±0.03 b	94±1 o
x-tra base VOCO (Bulk)	4	4.40±0.04 c	99±1 i,m

* Same superscript indicates products that performed similarly according to statistical analysis. Unmatched superscripts indicate products that performed differently than the others according to statistical analysis. (DOC one-way ANOVA: $p \leq 0.001$; Knoop hardness one-way ANOVA: $p > 0.05$).

† We did not measure DOC for HYPERFIL because it is dual cured, and DOC is not applicable to dual cure composites according to the standard test method ISO 4049-2009.[16]

‡ Bottom: top hardness ratio of 80 percent is considered to be adequate curing.[18]

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To assess the Knoop hardness, we prepared 10- mm–diameter composite disc specimens of varying depth (2-5 mm, depending on manufacturer's directions for use) in Teflon molds. We measured the composite disc's hardness by pressing a pointed indenter into the specimens at five places on each of the top and bottom surfaces. We then compared the average depth of the indentations on the bottom to those on the top. In this way, we obtained the hardness ratio of the two surfaces.

Results: We repeated the depth of cure test on three specimens each of the composites (with the exception of HYPERFIL). We performed the Knoop hardness test on five specimens for each composite. The mean results for each test are reported in Table 2 (page 14).

According to ISO 4049-2009, the depth of cure should be no more than 0.5 mm below the value stated by the manufacturer.[16] SonicFill, Tetric EvoCeram Bulk Fill, and Alert Condensable Composite did not pass the specification, while all others passed.

For the Knoop hardness test, a bottom-to-top hardness ratio of 80 percent is considered to be adequate curing.[18] All the products met this requirement, with the exception of the Alert Condensable Composite.

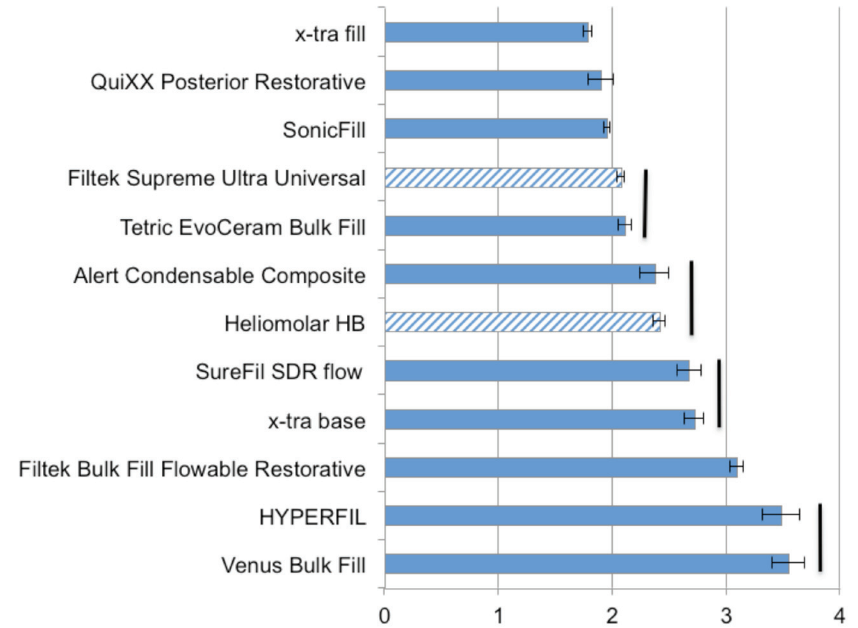
Volumetric Shrinkage

Clinical significance: Low volumetric shrinkage reduces the possibility of the composite pulling away from the tooth surface during polymerization, thereby reducing the potential for microleakage and marginal staining.

Methods: We used a contact angle-measuring instrument (Easy Drop System, model FM40, Krüss America, Charlotte, NC) to measure the volumetric shrinkage of the tested composites. We measured the volume of a 10 µl composite sample both before and after curing of each of the composites except HYPERFIL, the dual-cure composite. We used the difference in volume between pre-curing and 5-minute post-curing to calculate percentage volumetric shrinkage. Because HYPERFIL is a dual-cure composite, we applied the Archimedes principle to calculate its volumetric shrinkage.

Statistics: When analyzing results, we compared the mean shrinkage values using a Kruskal–Wallis test and found significant differences among the means ($p \leq 0.001$). We used post hoc Mann-Whitney U tests with the one-stage method multiple comparison procedure to correct for the False Discovery Rate (FDR) to compare multiple brands at $p<0.05$ see Figure 1.[19]

Results: We tested 10 specimens for each composite and report the mean percentage of volumetric shrinkage in Figure 1. For this test, lower values are preferred. VOCO's x-tra fill, which is a bulk-fill composite, showed the lowest volumetric shrinkage.



* Solid horizontal bars represent bulk filled composites. Striped horizontal bars represent incremental filled composites. Vertical black bars indicate products that performed similarly according to statistical analysis. Products that do not share a black bar had significantly different mean volumetric shrinkage.
† Lower values are preferred

Figure 1. Mean Percent Volumetric Shrinkage for Incremental vs. Bulk-Fill Composites (n=10).*†

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Polymerization Shrinkage Stress

Clinical significance: The restorative-tooth interface is constantly subjected to stress and strain imposed by polymerization shrinkage forces, thermal stimuli and functional occlusal loads. These stresses may result in clinical problems such as microleakage, marginal breakdown, fractures, postoperative sensitivity, staining and potential pulpal irritation.

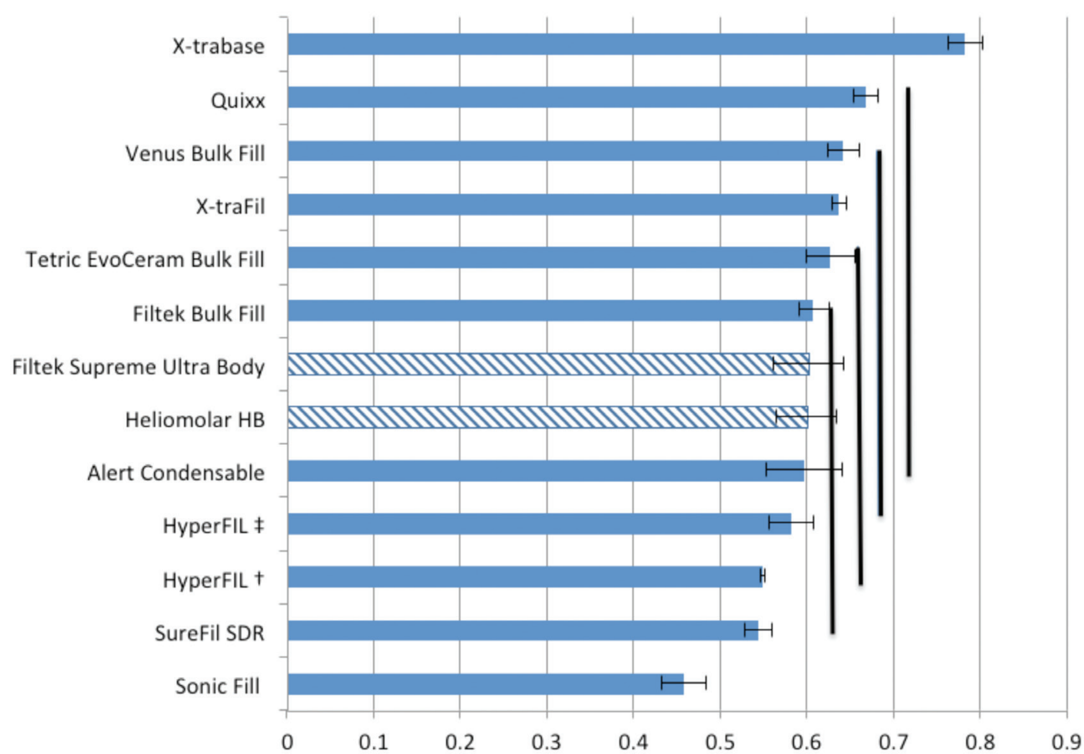
Methods: We performed the polymerization shrinkage stress test at Bisco Dental Inc. (Schaumburg, IL) using a device designed and built by Bisco. This device was designed to measure the contraction force at the bottom of a simulated class I cavity with a load cell in both light- and self-curing mode. We placed the uncured resin composite specimen into a cylindrical well with a lower plate that was attached to the load cell, which was sensitive to changes in force.

We coated the bottom surface and the wall of the cylindrical well that made contact with composite sample with Z-prime metal primer (Bisco Inc.), followed by a layer of Allbond 3 adhesive system (Bisco Inc.). The depth of the sample well was adjustable from 0 to 4.5 mm. Depths varied, depending on manufacturers' claimed increment thickness for each respective product.

When appropriate, we light cured specimens according to manufacturer recommendations (we tested both light-cure and chemical-cure formulations of HYPERFIL). We measured force continuously for 30 minutes and then converted force to stress (MPa) by dividing force by area. We calculated the configuration factor (C-factor) for each depth tested and normalized the shrinkage stress results based on the varying C-factors. The C-factor is the ratio of bonded surfaces to unbounded surfaces.

Statistics: Statistically, the shrinkage stress data was normally distributed (Shapiro-Wilk test $p = 0.1438$), so we used ANOVA to compare the means. Based on a value of $p < 0.0001$, at least one brand significantly differs from the rest, so a post hoc Tukey test with $p<0.05$ was used to determine which specific brands had significantly different shrinkage stress values.

Results: We tested three specimens of each composite at the manufacturer claimed depth of cure and report the mean results in Figure 2. Again, for this test, lower values were more desirable. The high viscosity SonicFill and flowable SureFil SDR flow had the lowest polymerization shrinkage stress among all the bulk-fill composites.



* Solid horizontal bars represent bulk filled composites. Striped horizontal bars represent incremental filled composites. The vertical black bar indicates products that performed similarly according to statistical analysis.
¶ Lower values are preferred.
§ Because HYPERFIL is a dual-cure composite, we applied the Archimedes principle to calculate its volumetric shrinkage. We used a contact angle-measuring instrument (Easy Drop System, model FM40, Krüss America, Charlotte, NC) to measure the volumetric shrinkage of the others.
† Chemical cure
‡ Light cure

Figure 2. Mean Polymerization Shrinkage Stress (MPa)/Configuration Factor for Incremental vs. Bulk-Fill Composites (n=3).*¶§

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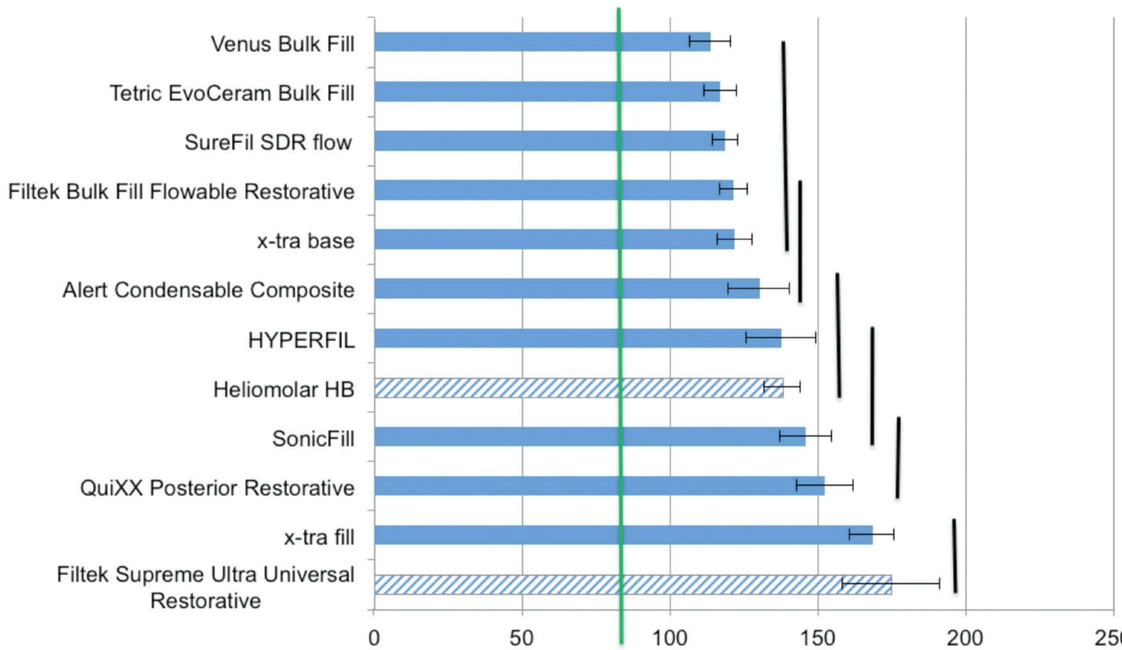
Flexural Strength and Flexural Modulus

Clinical significance: Flexural strength indicates whether a restoration can tolerate an occlusal load without fracturing. Flexural modulus is an indication of the material's stiffness. A high modulus means that the material is rigid and does not deform significantly under occlusal load.

Methods: For this test we prepared 10 specimens of each composite according to the international standard test method,[16] light cured them according to the manufacturers' instructions and stored them in a distilled water bath (37±1 °C) until the start of the test, which we conducted according to ISO 4049-2009 standard procedure.[16]



* Solid horizontal bars represent bulk-filled composites. Striped horizontal bars represent incremental-filled composites. Vertical black bars indicate products that performed similarly according to statistical analysis. Products that do not share a black bar had significantly different mean flexural strength.

† As indicated by the green bar, flexural strength according to ISO 4049 should be equal or greater than 80 MPa.[16]

Figure 3. Mean Flexural Strength (MPa) for Incremental vs. Bulk-Fill Composites (n=10).* †

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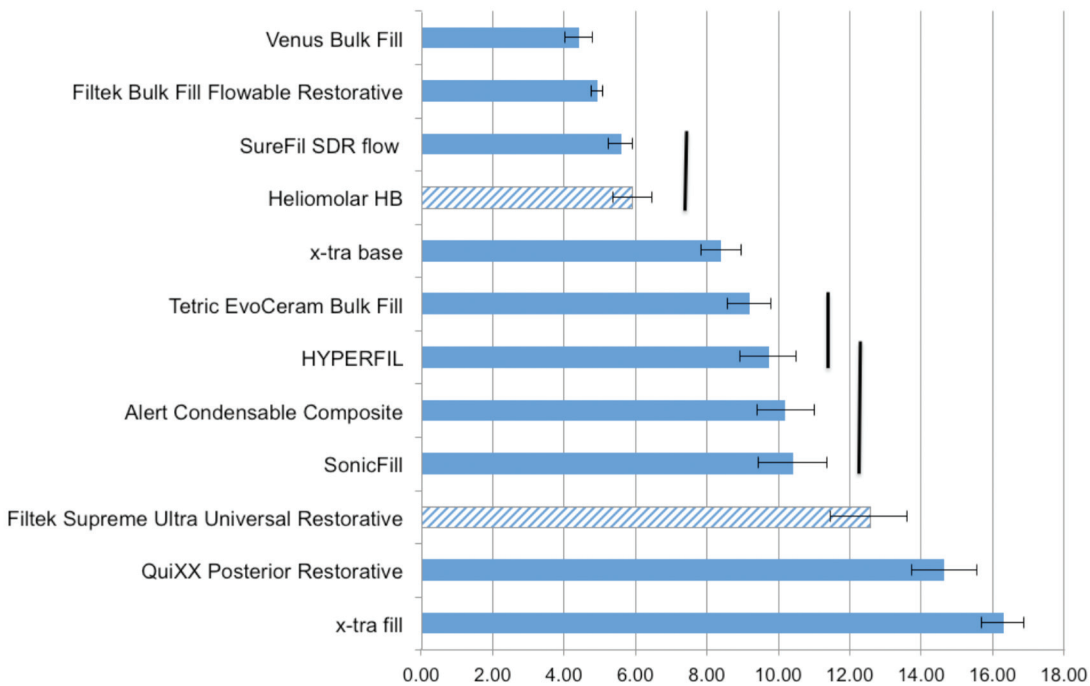
Statistics: Statistically, flexural strength is not a normally distributed variable (Shapiro-Wilk Normality test $p = 0.0001$), so we used a Kruskal-Wallis test and determined that the median flexural strength varied significantly by brand ($p < 0.0001$). We used post hoc Mann-Whitney U tests with corrections for FDR at $p < 0.05$ (Figure 3). Likewise, flexural modulus is not a normally distributed variable (Shapiro-Wilk Normality test $p = 0.0002$), so again, we used a Kruskal-Wallis and found that median flexural modulus differed significantly by brand ($p < 0.0001$). We used post hoc Mann-Whitney U tests with FDR corrections to compare the brands at $p < 0.05$ (Figure 4).

Results: Figure 3 shows the mean flexural strengths of all tested materials, and Figure 4 shows the mean flexural modulus. For flexural strength, higher values are preferred. The desired value for flexural modulus varies depending on the type of restoration being placed. All of the products had adequate flexural strength according to ISO 4049-2009, which requires a value of at least 80 MPa.[16]



* Solid horizontal bars represent bulk filled composites. Striped horizontal bars represent incremental filled composites. Vertical black bars indicate products that performed similarly according to statistical analysis. Products that do not share a black bar had significantly different mean flexural modulus.

Figure 4. Mean Flexural Modulus (GPa) for Incremental vs. Bulk-Fill Composites (n=10).*

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Fracture Toughness and Fracture Work

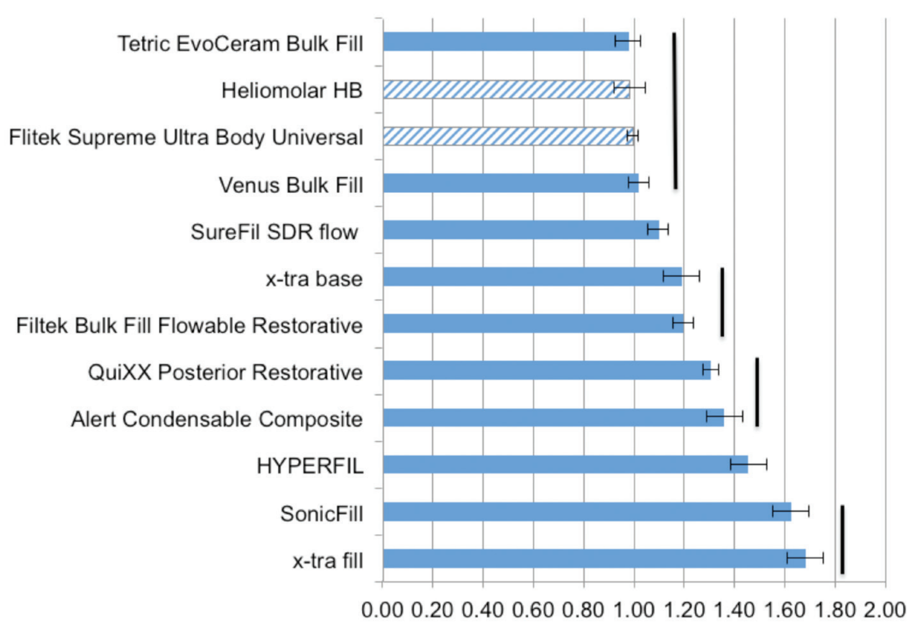
Clinical significance: The ability of a restorative material to withstand fracture is crucial, especially in stress-bearing areas. The high fracture toughness value of a restorative material may be one of the factors contributing to a favorable clinical outcome in high stress-bearing areas. Fracture work provides an indication of a restoration's ability to resist failure caused by the growth of a crack. Fracture work is the total amount of energy required to "grow" the crack through the specimen to complete fracture. This is calculated from the test performed for fracture toughness and expressed in terms of surface energy in joules per square meter.

Methods: We used a test method developed in the ADA Laboratories to determine fracture toughness and fracture work. We based this method on established international standards.[20-23] We used Delrin (DuPont) split molds (34 mm X 4 ± 0.13 mm X 3 ± 0.13 mm) to make 10 specimens (sizes from Annex A.2 ASTM-C1421)[22] for each composite material. A starter notch approximately 1.0 mm X 0.5 mm wide was sawed into each specimen. We then used an abrasive wheel-sharpened circular blade to extend the starter notch to the desired crack length (1.4 to 1.6 mm) and sharpness (tip <20 micrometers diameter). We used a profile projector to measure the sharpness and length of the V-notch before and after fracture. After 24 ± 2 hours in distilled-water at 37 ± 1 °C, specimens were loaded until failure in a three-point-bending apparatus at a cross-head speed of 0.5 mm/min using a mechanical test machine. We measured the fractured surface in three places to yield an average-crack-length (a). We used standard equations[21] for three-point-loading given with conditions of $0.35 \leq (a)/(W) \leq 0.70$ (W=width, a=average crack length) to calculate fracture toughness and work.

Statistics: Statistically, fracture toughness is not a normally distributed variable (Shapiro-Wilk normality test, $p < 0.0001$), so we used the Kruskal-Wallis test to determine whether the median fracture toughness differed significantly by brand. Based on a value of $p < 0.0001$, at least one brand significantly differs from the rest. We used post hoc Mann-Whitney U tests with correction for FDR to compare the brands at $p < 0.05$ (Figure 5 on page 20). Fracture work, likewise, is not a normally distributed variable (Shapiro-Wilk normality test $p = 0.006$), so we used a Kruskal-Wallis test to determine whether the median fracture work differed significantly by brand.

Based on a value of $p < 0.0001$, at least one brand significantly differs from the rest, so post hoc Mann-Whitney U tests with FDR corrections were used to compare the brands at $p < 0.05$.

Results: Fracture toughness and fracture work mean values are shown in Figures 5 and 6, respectively, for all materials tested. For both fracture toughness and fracture work, higher values are preferred.



* Solid horizontal bars represent bulk-filled composites. Striped horizontal bars represent incremental-filled composites. Vertical black bars indicate products that performed similarly according to statistical analysis. Products that do not share a black bar had significantly different mean fracture toughness.
† Higher values are preferred.

Figure 5. Mean Fracture Toughness (MPa-m^0.5) for Incremental vs. Bulk-Fill Composites (n=10)* †

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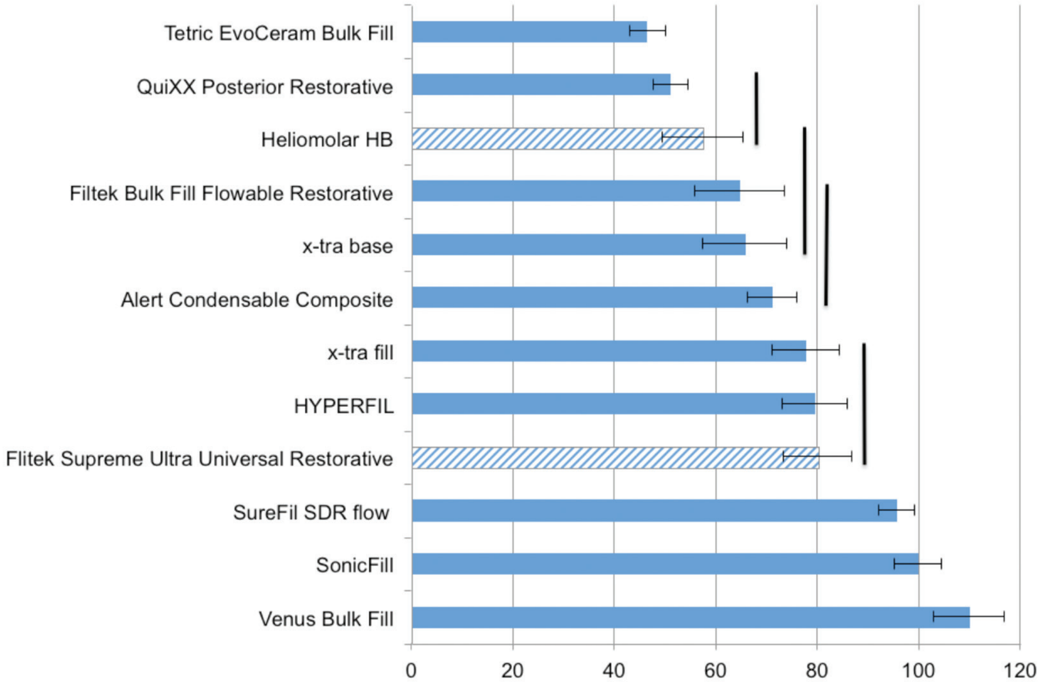
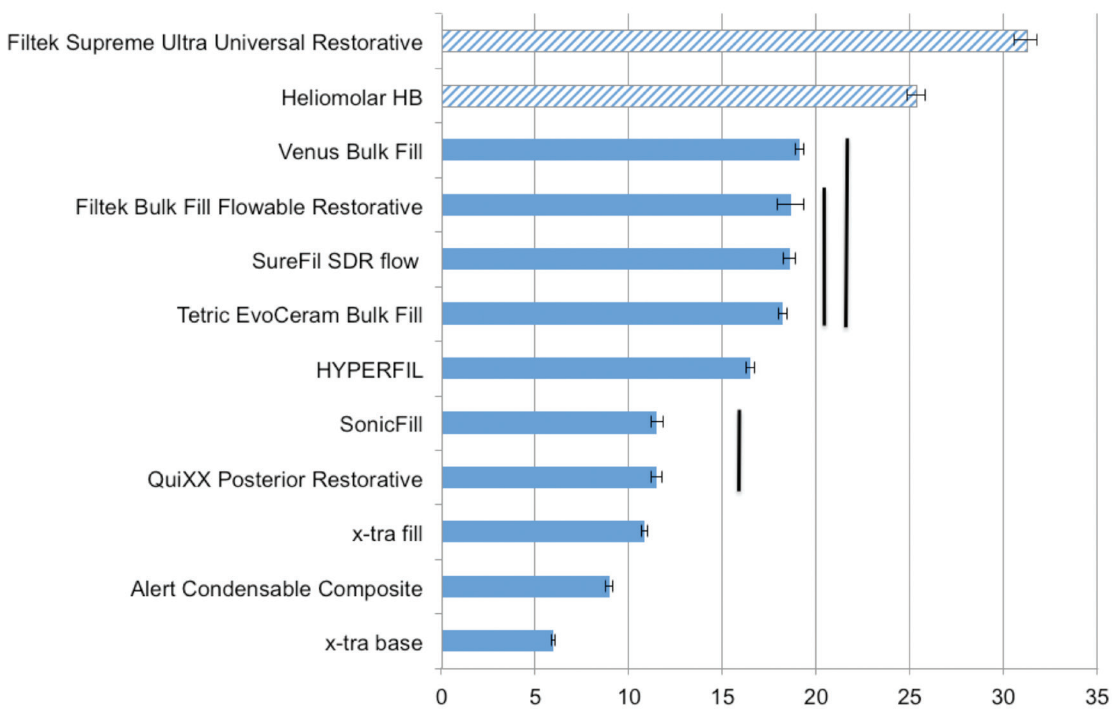


* Solid horizontal bars represent bulk-filled composites. Striped horizontal bars represent incremental-filled composites. Vertical black bars indicate products that performed similarly according to statistical analysis. Products that do not share a black bar had significantly different mean fracture work.
† Higher values are preferred.

Figure 6. Mean Fracture Work (J/m^2) for Incremental vs. Bulk-Fill Composites (n=10)* †



* Solid horizontal bars represent bulk-filled composites. Striped horizontal bars represent incremental-filled composites. Vertical black bars indicate products that performed similarly according to statistical analysis. Products that do not share a black bar had significantly different mean water sorption.
† The maximum water sorption value recommended for restorative materials is 40µg/mm^3, according to ISO 4049.[16] Water sorption for all tested products fell below this value.

Figure 7. Mean Water Sorption (µg/mm^3) of Incremental vs. Bulk-Fill Composites (n=5).* †

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Water Sorption and Solubility

Clinical significance: Water sorption could lead to dimensional changes, loss of retention, staining and breaking in margin contours. The solubility of dental restoratives influences the rate of degradation and the biological compatibility.

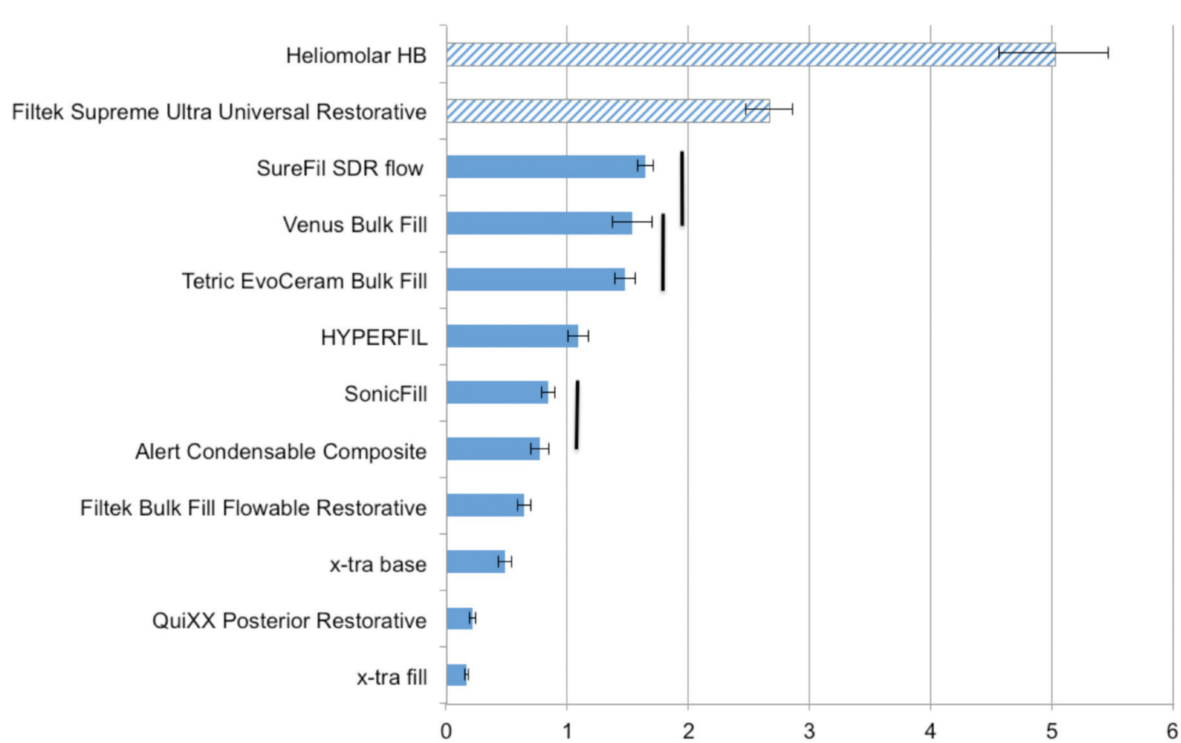
Methods: Using standard test methods,[16,23] we prepared five disc-shaped specimens of each composite material according to manufacturers' instructions and placed them in a desiccator maintained at 37 ± 1 °C. After 22 hours, we moved the specimens to a second desiccator maintained at 23 ± 1 °C for 2 hours and then weighed them to an accuracy of ±0.1mg(mass 1), repeating this cycle until we achieved a constant mass. Once the specimens were sufficiently dried, we measured them and calculated the volume of each.

We immersed these specimens in a water bath maintained at 37 ± 1 °C for 30 days. After that time, we washed the specimens with water, blotted away any surface moisture and waved them in the air for 15 seconds. One minute after removing them from the water, we reweighed the samples (mass 2). We then placed them in the desiccators, and using the cycle described previously, we dried them to a constant mass (mass 3).

Statistics: Statistically, water sorption is not a normally distributed variable (Shapiro-Wilk normality test $p = 0.0013$), so we used a Kruskal-Wallis test to determine whether the median water sorption values differed significantly by brand. Based on a value of $p < 0.0001$, at least one brand significantly differed from the rest. We used post hoc Mann-Whitney U tests with FDR correction at $p < 0.05$ (Figure).

Likewise, water solubility is not a normally distributed variable (Shapiro-Wilk normality test $p < 0.0001$), so we again used a Kruskal-Wallis test to determine whether the median water sorption values differed significantly by brand. Based on a value of $p < 0.0001$, at least one brand significantly differed from the rest, so post hoc Mann-Whitney U tests with FDR corrections at $p < 0.05$ were used to determine which brands were significantly different from each other.

Results: Water sorption and water solubility were calculated for all composite materials tested, and their mean values are shown in Figures 7 and 8, respectively. For both water sorption and solubility, lower values are preferred.



* Solid horizontal bars represent bulk-filled composites. Striped horizontal bars represent incremental-filled composites. Vertical black bars indicate products that performed similarly according to statistical analysis. Products that do not share a black bar had significantly different mean water solubility.

† The maximum water solubility value recommended for restorative materials is 7.5μg/mm³, according to ISO 4049.[16] Water solubility for all tested products fell below this value.

Figure 8. Mean Water Solubility (μg/mm³) of Incremental vs. Bulk-Fill Composites (n=5).*†

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Shade and Color Stability

Clinical significance: This test verifies that the composite restoration will maintain its color in wet and dry environments.

Methods: To measure shade and color stability, we followed a standard test method, which included comparisons to the shade guides provided by the manufacturers.[16,23] Three independent observers assessed the shade stability of the shaded composites.

Table 3. Shade Stability of Incremental vs. Bulk-Fill Composites Dry Specimens (n=5).*

Product (Shade) Manufacturer (Recommended placement method)	No Change	Slightly Perceptible Change	Perceptible Change
Traditional Universal Composites			
Filtek Supreme Ultra Universal Restorative (A2) 3M ESPE (Incremental)		X	
Heliomolar HB (A2) Ivoclar Vivadent, Inc. (Incremental)	X		
Bulk Fill Composites			
Alert Condensable Composite (A2) Pentron (Bulk)	X		
HYPERFIL (U) Parkell, Inc. (Dual cure: incremental or bulk)	N/A†		
QuiXX Posterior Restorative (U) Dentsply (Bulk)	N/A		
SonicFill (A2) Kerr (Bulk)		X	
Tetric EvoCeram Bulk Fill (IVA) Ivoclar Vivadent, Inc. (Bullk)	N/A		
x-tra fill (U) VOCO (Bulk)	N/A		
Bulk Fill Flowables			
Filtek Bulk Fill Flowable Restorative (A2) 3M ESPE (Bulk)	X		
SureFil SDR flow (A2) Dentsply Caulk (Bulk)	X		
Venus Bulk Fill (U) Heraeus (Bulk)	N/A		
x-tra base (A2) VOCO (Bulk)	X		

* After 30-day storage in a dry area at 37°C versus shade guide, according to three independent observers.
† N/A: Because the universal shaded composites had no shade guide for comparison, only the shaded composite resin specimens were tested for the shade test.

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Since the universal shades did not have guides from the manufacturers to compare against, we only evaluated shade stability for those composites. We assessed color stability for all of the composites.

Results: See Tables 3-5 for results concerning shade and color stability. All the tested products showed little or no variation for shade and color stability after 30 days water storage except Tetric EvoCeram Bulk Fill (IVA) and x-tra fill (U), which showed perceptible change in color stability after 30 days in water at 37°C.

Table 4. Shade Stability of Incremental vs. Bulk-Fill Composites Wet Specimens (n=5).*

Product Shade Manufacturer (Recommended placement method)	No Change	Slightly Perceptible Change	Perceptible Change
Traditional Universal Composites			
Filtek Supreme Ultra Universal Restorative (A2) 3M ESPE (Incremental)		X	
Heliomolar HB (A2) Ivoclar Vivadent, Inc. (Incremental)	X		
Bulk Fill Composites			
Alert Condensable Composite (A2) Pentron (Bulk)		X	
HYPERFIL (U) Parkell, Inc. (Dual cure: incremental or bulk)	N/A†		
QuiXX Posterior Restorative (U) Dentsply (Bulk)	N/A		
SonicFill (A2) Kerr (Bulk)		X	
Tetric EvoCeram Bulk Fill (IVA) Ivoclar Vivadent, Inc. (Bulk)	N/A		
x-tra fill (U) VOCO (Bulk)	N/A		
Bulk Fill Flowables			
Filtek Bulk Fill Flowable Restorative (A2) 3M ESPE (Bulk)		X	
SureFil SDR flow (A2) Dentsply Caulk (Bulk)	X		
Venus Bulk Fill (U) Heraeus (Bulk)	N/A		
x-tra base (A2) VOCO (Bulk)		X	

*After 30-day storage in a wet area at 37°C versus shade guide, according to three independent observers.
†N/A: Because the universal shaded composites had no shade guide for comparison, only the shaded composite resin specimens were tested for the shade test.

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Radiopacity

Clinical significance: This test demonstrates the ability to identify the composite on a radiograph and differentiate it from tooth structure.

Methods: Using disc-shaped composite specimens (1.0 ± 0.1mm thick) and an aluminum step wedge with a thickness that ranged from 0.5 mm to 5.0 mm, we measured the radiopacity of each composite according to a standard test method.[16,23] We irradiated a film for each specimen set next to the step wedge with X-rays at 65 ± 5kV and a target film distance of 300 mm to 400 mm for such a time that, after processing, the region of film beside the specimen and aluminum has an optical density between 1.5 and 2 mm Al. We then measured the optical density of the specimen image and that of each step of the aluminum. Based on these measurements, we used a standard method to calculate the radiopacity of each specimen.[16,23]

Statistics: Radiopacity is a normally distributed variable (Shapiro-Wilk normality test p=0.08), so we used ANOVA to determine if the means differed significantly by brand. Based on a value of $p < 0.0001$, at least one brand significantly differs from the rest, so a post hoc Tukey test with $p < 0.05$ was used to determine which specific brands had significantly different radiopacity values.

Table 5. Color Stability of Incremental vs. Bulk-Fill Composites Upon Water Sorption (n=5).*

Product Shade Manufacturer (Recommended placement method)	No Change	Slightly Perceptible Change	Perceptible Change
Traditional Universal Composites			
Filtek Supreme Ultra Universal Restortive (A2) 3M ESPE (Incremental)		X	
Heliomolar HB (A2) Ivoclar Vivadent, Inc. (Incremental)	X		
Bulk Fill Composites			
Alert Condensable Composite (A2) Pentron (Bulk)		X	
HYPERFIL (U) Parkell, Inc. (Dual cure: incremental or bulk)	X		
QuiXX Posterior Restorative (U) Dentsply (Bulk)		X	
SonicFill (A2) Kerr (Bulk)	X		
Tetric EvoCeram Bulk Fill (IVA) Ivoclar Vivadent, Inc. (Bulk)			X
x-tra fill (U) VOCO (Bulk)			X
Bulk Fill Flowables			
Filtek Bulk Fill Flowable Restorative (A2) 3M ESPE (Bulk)		X	
SureFil SDR flow (A2) Dentsply Caulk (Bulk)		X	
Venus Bulk Fill (U) Heraeus (Bulk)		X	
x-tra base (A2) VOCO (Bulk)		X	

* After 30-day storage in a dry area at 37°C versus 30-day storage in a wet area at 37°C, according to three independent observers.

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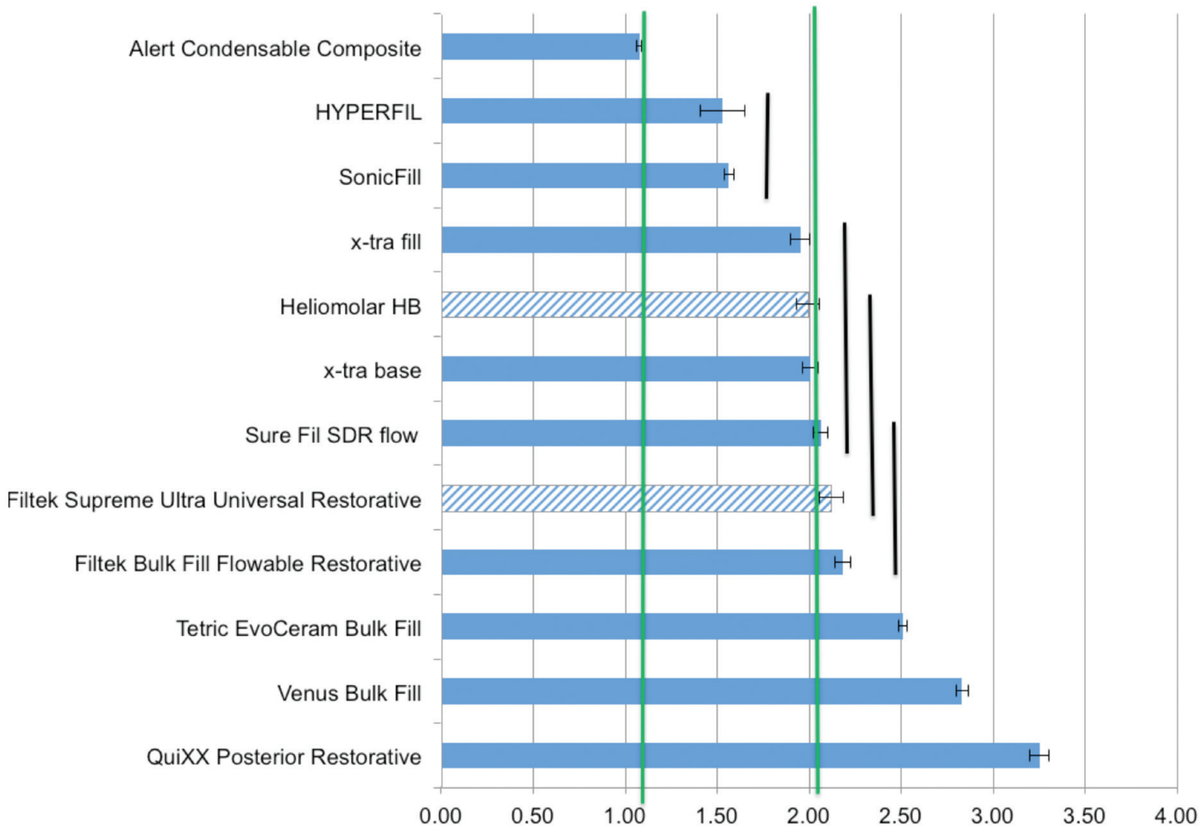
Results: The average radiopacity of dentin is equivalent to 1.11 mmAl and enamel is equivalent to 2.05 mmAl.[24] All tested products exhibited a radiopacity value greater than 1 mmAl (Figure 9), which is required by the standard.[16]

Summary

This evaluation compared several properties of bulk-fill versus multi-increment–fill, resin-based composites and found performance of restoratives in both categories to be acceptable according to an international standard,[16] with the exception of depth of cure and hardness. Three of the bulk-fill resin-based composites did not achieve adequate depth of cure when tested according to the standard (SonicFill, Tetric EvoCeram Bulk Fill, and Alert Condensable Composite). All products but one (Alert Condensable Composite) demonstrated adequate hardness after curing in a subsequent test (Knoop hardness test).

With the exception of depth of cure and Knoop hardness, we found the laboratory performance of bulk-fill resin-based composites to be comparable to that of traditional multi-increment–fill resin-based composites.



* Solid horizontal bars represent bulk-filled composites. Striped horizontal bars represent incremental-filled composites. Vertical black bars indicate products that performed similarly according to statistical analysis. Products that do not share a black bar had significantly different mean radiopacity.

† As indicated by the green vertical bars, radiopacity for a 1-mm sample of dentin is 1.11mmAl and enamel is 2.05mmAl.[23]

Figure 9. Mean Radiopacity (mm Al) of Incremental vs. Bulk-Fill Composites (n=3).*†

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