STATISTICAL ANALYSIS OF ACOUSTIC EMISSIONS DURING SHRINKAGE OF RESTORATION IN DENTAL SUBSTRATE

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Keywords: *Composite restoration, Acoustic emission, Non-parametric statistics*

1 Introduction

Evaluation of marginal integrity at the composite resin-tooth interface is required for clinically successful restorations. Polymerization contraction of the composite resin that fills in a cavity occurs during light curing. This contraction competes with the bond strength and may cause marginal disintegration. There can be some unbonded state and/or cleavage formation around the margin of the composite resin part, leading to insufficient sealing of open dentinal tubules[1]. Various experiments such as SEM and dye penetration test[2] have been performed for observing the marginal gap along the composite resin-tooth interface. These studies did not show any temporal analysis of debonding mechanisms. The present authors investigated the fracture process of composite/tooth by an acoustic emission (AE) monitoring in real-time[3]. The AE data that was newly obtained needs to be differentiated according to various test conditions. In this study, a non-parametric statistic is applied to verify the difference of AE amplitudes and AE hits depending on substrate kinds and adhesive conditions.

2 Non-parametric statistical tests

2.1 Mann-Whitney test

The Mann-Whitney test[4] is a non-parametric statistical hypothesis test for assessing whether two independent samples for observations show equality values. First, the null hypothesis that the medians of the first population and the second population are equal is established. Each data rank is sought through a sum of two population samples. Equations (1) and (2) indicate the mean value(E) and the variation(V) of the test statistic W. The p-value (significance probability) is calculated by Eqs.(1) and (2).

$$\mathrm{E(W)} = \frac{n_1(\mathrm{N}+1)}{2} \tag{1}$$

$$\mathrm{V(W)} = \frac{n_1 n_2(\mathrm{N}+1)}{12} \tag{2}$$

$$\mathrm{p-value} = 2\Phi\left(\frac{\mathrm{W}-\mathrm{E(W)}+0.5}{\sqrt{\mathrm{V(W)}}}\right) \tag{3}$$

where, n_1: the number of sample 1, n_2: the number of sample 2, $N=n_1+n_2$.

2.2 Kruskal-Wallis test

Kruskal-Wallis test[5] is a non-parametric statistical test for testing the equality of population medians among three or more groups. The test statistic H is calculated by equation (4) with the rank of each data (R_i).

$$H = \frac{12}{N(N+1)}\sum_{i=1}^{k}\frac{R_i^2}{n_i} - 3(N+1) \tag{4}$$

where, n_i: the number of sample in i^{th} population, N: sum of total samples, R_i: the rank of sample in i^{th} population.

$$\mathrm{p-value} = 1 - \chi^2(\mathrm{k}-1, \mathrm{H}) \tag{5}$$

The p-value is approximated by equation (5).

3 Experimental

3.1 Acoustic emission measurement

Non-penetration ring type substrates(inner diameter 6mm, outer diameter 8mm, depth 2mm, height 3mm) were prepared. Three substrate materials of stainless steel, PMMA and human tooth were adopted. The human tooth specimen was made as shown Fig.1.

Fig. 1 Preparation of the human tooth specimen

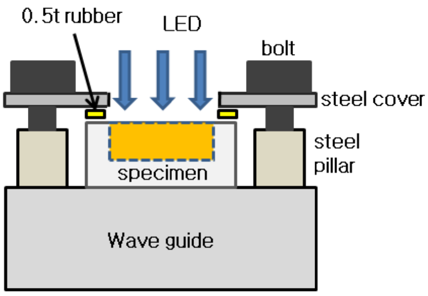

Fig. 2 Schematic of specimen fixture for acoustic emission measurement

The extracted tooth was mounted on the bottom. The liquid polymer was filled in a short plastic pipe and then fixed by curing. For comparison of bonding quality, rings without adhesive coating as well as rings with adhesive coating, but not exposed by the LED light, were also prepared. The specimen was mounted on the wave guide steel plate using specially designed mechanical fixture(Fig.2). An AE sensor (micro30, Physical Acoustic Corp.) having a detectable frequency range of 100–600 kHz with a peak sensitivity at 250 kHz was also mounted on the steel plate with a close distance of 15mm from the ring specimen. The vacuum grease coupled the sensor and the plate. AE measurement conditions were a pre-amp of 40 dB, a threshold level of 25 dB and a sampling rate of 4 MHz. From this AE test, the AE hits and the amplitudes were measured.

3.2 Statistical analysis

The AE hits and AE amplitudes were analyzed statistically by the Kruskal-Wallis test and Mann-Whitney test. The Mann-Whitney test is conducted to investigate the significance between two groups. The Kruskal-Wallis test is conducted to investigate significance among more than two groups. All statistical tests were performed at a 95% level of confidence.

3.3 Microscopic examination of the marginal disintegration

After the strain measurement and the acoustic emission detection of the composite resin restorations, the ring and human molar specimens were consolidated into a plastic mold. The top parts of the specimens were slightly sectioned, and then were ground and polished with buff and abrasive alumina powder. The polished surfaces were observed by optical and SEM to examine the marginal disintegration and gap formation states around the margin of the composite restorations. The gap thickness and the gap percentage at the margin of the composite resin were measured. The gap percentage was obtained from the summation of the gap lengths formed along the margin over the inner periphery of the ring substrate.

4 Results and Discussion

4.1 Detection of AE parameter

Table 1 shows the number of AE hits, the peak amplitude and initial generation time of AE for the good bonding state. The quantity of AE hits for the human tooth substrate was much less than that for the steel substrate but more than that for the PMMA substrate. The amplitude and initial generation time of AE, however, was difficult to distinguish clearly according to substrate materials. Fig. 4 shows the number of AE hits and amplitude for the human tooth substrate according to the bonding conditions. The number of AE hits for good bonding state was less than for bad bonding state. However, based on the mean values of AE hits and the amplitudes, it was hard to differentiate the bonding conditions due to large deviations in AE data. For the classification, a statistic comparison of measured AE parameters is needed on various experimental conditions.

Table 1 AE hit events and amplitude for various substrate ring specimens

Materials	AE hits	Amplitude (dB)	t_{ini} (sec)
PMMA	1.89±1.17	36.08±5.73	19.23±16.88
Human tooth	6.75±1.50	31.94±3.92	43.18±48.78
Stainless steel	12.00±3.39	34.83±10.53	25.00±23.60

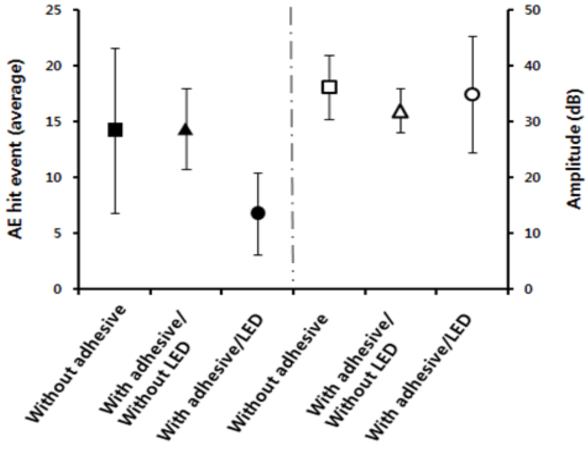

Fig. 3 Results of AE hit events and amplitude for the human molar dentin specimens

4.2 Significance analysis for AE hit data

Table 2 shows the AE hits and their statistical results according to ring substrate in the good bonding state with adhesive and LED. The number of AE hits revealed statistically significant differences from both Mann-Whitney and Kruskal-Wallis tests ($p<0.05$). Table 3 shows the AE hits and statistical results according to different adhesive conditions. Statistical difference was observed between good bonding state and bad bonding state for PMMA substrate ($p<0.05$; Mann- Whitney test). Similarly for human tooth substrate, statistical difference was observed between good bonding state and bad bonding state ($p<0.05$; Mann-Whitney test). The AE hits were not statistically significant for bad states of PMMA and human tooth substrate. Meanwhile, statistical difference was not observed between good bonding state and bad bonding state for stainless steel substrate ($p>0.05$; Mann-Whitney test). On Kruskal-Wallis test, the number of AE hits showed significant results in all substrate ($p<0.05$).

PMMA had high bond strength with the adhesive for a good restoration. PMMA ring was compressible due to its low stiffness. These advantages brought about little cracking, and led to less detection of AE events for PMMA substrate. Many AE events, meanwhile, were detected for stainless steel substrate since stainless steel had high stiffness and poor bonding state. Human tooth substrate etched by a bonding agent combined well

Table 2 AE hits and statistical result according to different substrate

Materials	n	AE hit events (mean±S.D)	Mann-Whitney (p-value)		Kruskal-Wallis (p-value)
PMMA	7	1.89±1.17	0.0058		
Tooth	4	6.75±1.50		0.0029	0.002
Stainless steel	7	12.00±3.39	0.0342		

Table 3 AE hits and statistical results according to different adhesive conditions

	Adhesive condition	n	AE hit events (mean±S.D)	Mann-Whitney (p-value)		Kruskal-Wallis (p-value)
PMMA	Without adhesive	9	4.33±0.87	0.2734		
	With adhesive/without LED	7	3.86±1.57		0.0018	0.013
	With adhesive/LED	7	1.89±1.17	0.0174		
Human tooth	Without adhesive	5	14.20±7.40	0.3591		
	With adhesive/without LED	6	14.33±3.67		0.0262	0.029
	With adhesive/LED	4	6.75±3.67	0.0136		
Stainless steel	Without adhesive	10	20.60±7.62	0.0339		
	With adhesive/without LED	7	12.83±3.71		0.0231	0.021
	With adhesive/LED	7	12.00±3.39	0.7823		

Table 4 AE amplitude and statistical results according to different adhesive conditions

	Adhesive condition	AE amplitude (dB) (mean±S.D)	Mann-Whitney (p-value)		Kruskal-Wallis (p-value)
PMMA	Without adhesive	33.43±6.97	0.949		
	With adhesive/Without LED	33.87±7.02		0.479	0.702
	With adhesive/LED	31.88±6.42	0.439		
Human tooth	Without adhesive	36.08±5.73	0.569		
	With adhesive/Without LED	31.94±3.92		0.569	0.773
	With adhesive/LED	34.83±10.53	0.728		
Stainless steel	Without adhesive	33.59±11.54	0.038		
	With adhesive/Without LED	33.90±9.62		0.001	0.002
	With adhesive/LED	31.95±13.60	0.031		

with a composite resin restoration. Because the human tooth substrate has higher stiffness than PMMA, AE events were more detected than PMMA.

4.3 Significance analysis for AE amplitude

Table 4 shows the AE amplitude and statistical results according to various adhesive conditions. For PMMA and human tooth substrate, since most of hits corresponded to the low amplitudes 25-40dB regardless of adhesive conditions, amplitudes were not significant ($p>0.05$). For stainless steel without adhesive, however, the high amplitude emissions above 40dB were detected. In this case, statistical difference was observed clearly depending on adhesive conditions ($p<0.05$; Mann-Whitney and Kruskal-Wallis test).

4.4 Significance analysis for marginal gaps

Fig. 5 shows the overall relation of the total AE hits versus the marginal gap data. The total hits increased steeply with an increase in the maximum gap thickness and/or the gap percentage at the margin. It is thought that such a large variation of hits with the gap data can be used as a nondestructive evaluation index for marginal disintegration.

5 Conclusions

AE amplitudes and AE hits measured during composite resin restoration were compared through the non-parametric statistics of Mann-Whitney method and Kruskal-Wallis method according to various adhesive conditions and substrates. The statistical results showed that it was possible to differentiate the interfacial fracture of human tooth/composite restoration by using acoustic emission.

Acknowledgement

This work was supported by Grant No.2010-0016698 from the Basic Research Program of the National Research Foundation of Korea.

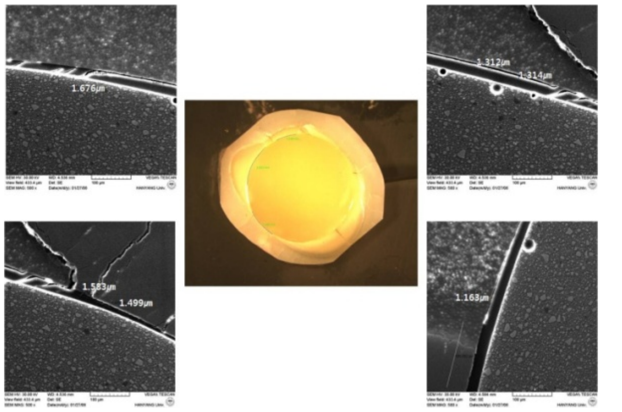

Fig. 4 SEM taken from the marginal region of composite restoration in a human tooth ring

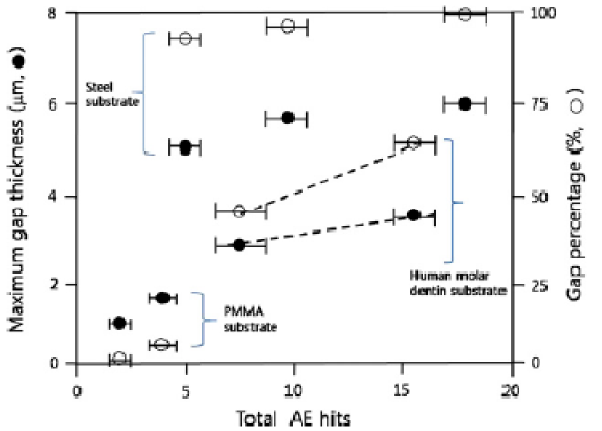

Fig. 5 Total AE hits as a function of the maximum gap thickness and the gap percentage for all kinds of tested specimens

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