Original Article

In vitro and *in vivo* Comparison of Orthodontic Indirect Bonding Resins: A Prospective Study

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Abstract

Objective: The aim of this study was to evaluate *in vitro* shear bond strength (SBS) and *in vivo* bond survival rates of brackets bonded using orthodontic indirect bonding resins. **Materials and Methods:** For the *in vitro* study, the first group was direct bonding control group. In Groups II and III, bonding was performed with indirect bonding resins that were either chemically or light-cured. The SBS of each sample was examined. For the *in vivo* study, full-mouth brackets were placed in 20 patients using a split-mouth approach, with either chemically-cured or a light-cured indirect bonding resin. The patients were followed for 12 months. Data were statistically evaluated using analysis of variance, Tukey's tests, and Weibull survival analysis. **Results:** The mean SBS values (MPa) were 17.6 ± 6.6, 13.1 ± 4.7, and 15.1 ± 5.9 for Group I, Groups II, and III, respectively, ($P < 0.05$). The adhesive remnant index scores of the groups were generally Score 3 and Score 4. *In vivo* follow-up showed no statistically significant differences in total bond failure rate between groups ($P > 0.05$). **Conclusions:** *In vitro* study showed lower SBS with chemically-cured indirect bonding resin than flowable light-cured resin and the control group, but *in vivo* failure rates of both indirect resins were found to be adequate for clinical usage.

Keywords: *In vivo survival, orthodontic adhesive, orthodontic indirect bonding, orthodontic resin, shear-bond testing*

Date of Acceptance:
20-Nov-2017

Introduction

The direct bonding of the fixed orthodontic appliances has been commonly used in clinical orthodontics, but there are some limitations of the direct technique. Indirect bonding of the brackets has several advantages, including improved patient comfort, more accurate bracket positioning, reduced chair time, and reduced operator stress.[1-3] Furthermore, indirect bonding of the brackets is important in lingual orthodontics because of the great anatomical differences of lingual surfaces and difficulty of the visualization.[4] However, most orthodontists shun this technique owing to its disadvantages, which include high laboratory costs, complex laboratory work, and the technical expertise which is required to achieve precise bonding.[5]

Thomas introduced a simple indirect bonding technique; in the laboratory stage, brackets were bonded on the plaster dental models with chemically-cured resin and in clinical stage brackets were carried to the mouth by a transfer tray.[6] Several investigators tried to modify the original Thomas Technique to elevate the bond strength of the indirect bonding technique to match that of direct bonding technique.[7-10]

Previous studies have compared shear bond strength (SBS) values for indirect and direct orthodontic bonding techniques.[11-14] Both Klocke *et al*. and Yi *et al*. found no significant differences between direct bonding and indirect bonding. However, most clinicians consider that indirectly bonded brackets have lower bond strength and higher bracket failure rates than directly bonded brackets.[15,16]

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Access this article online

Quick Response Code:

Website: www.njcponline.com

DOI: 10.4103/njcp.njcp_252_17

How to cite this article: Pamukçu H, Özsoy ÖP, Dağalp R. *In vitro* and *in vivo* comparison of orthodontic indirect bonding resins: A prospective study. Niger J Clin Pract 2018;21:614-23.

A recent study concluded that the prevalence of indirect bonding among clinicians is 18% and adhesives developed specifically for indirect bonding are increasing in demand.[17] Choosing the best contemporary resin for the indirect bonding could help the clinicians and would be useful for widespread use of indirect bonding technique. Thus, the first aim of this study was to compare the *in vitro* SBS of chemically-cured and light-cured flowable indirect bonding resin both with each other and a light-cured direct bonding resin. The second aim was to evaluate 12-month *in vivo* bond survival rates for indirectly bonded brackets to validate their usage in clinical practice.

Our first null hypothesis was there would be no difference between the direct and indirect bonding resins for SBS, and the second null hypothesis was the indirect bonding resins have adequate bond survival rates *in vivo*.

Materials and Methods

This study was carried out in accordance with the tenets of the Declaration of Helsinki and before initiation of both the *in vitro* and *in vivo* parts of the study, legal approval was received from the institutional review board and ethics committee of Baskent University (references D-KA 14/07 and D-DA 14/08).

Using the data from a previous article by Cal-Neto *et al*.,[18] it was assumed that to detect a difference of 5 MPa is clinically significant between groups. Using this data with a standard deviation of 4.55, it was determined that sample size was 23 teeth per group would be sufficient to provide a 5% significance level and 80% power, for *in vitro* part of the study. Assuming possible sample loss during the procedure, 25 teeth were assigned to each group. A total number of 75 human premolars were used for *in vitro* part of the study.

The sample size for *in vivo* part of the study was based on the number of teeth needed to demonstrate statistically significant differences between two different adhesives' bond failure rates. A previous study[13] with a similar split-mouth design estimated a mean 4% failure rate for both indirect bonding groups. The sample size assumed this study was two samples of 214 teeth bonded with each bonding adhesive which had 85% power with a standard deviation of 4.5, at 95% confidence level to detect a reduction in failure rate from 6% to 2% for two indirectly bonded groups. These 214 teeth per group (total = 428) correspond to approximately 18 patients and assuming possible fall-out, 20 patients were included to *in vivo* part of the study.

However, it is admitted that the analysis was based on quadrants which were depended units within individuals, and this is a result of the split-mouth studies.

Figure 1 shows the flowchart of the study. All *in vitro* and *in vivo* procedures were performed by the same clinician to eliminate technical differences in the bonding protocol.

Properties of the adhesives

Three different adhesives were used in this *in vivo* and *in vitro* study.

A direct-bonding, light-cured, highly filled orthodontic adhesive, (Transbond XT, 3M Unitek, Monrovia, CA, USA) was used in the control group for *in vitro* study. This resin contains 77% quartz-silica fillers. Due to this content, resin has a low penetration to enamel. A primer must be applied to enamel before the application of resin for increasing the adhesion. An adhesive primer (Transbond XT primer, 3M Unitek, Monrovia, CA, USA) was applied to the enamel according to the manufacturer's recommendations.

A chemically-cured indirect bonding adhesive (Transbond IDB, 3M Unitek, Monrovia, CA, USA) was used for *in vitro* and *in vivo* study. This adhesive is composed of 98% organic materials, and the filler content is very low, which allows the resin to have a better penetration on the enamel.

A light-cured flowable, moderately filled indirect bonding adhesive (Transbond Supreme LV, 3M Unitek, Monrovia, CA, USA) was used for *in vitro* and *in vivo* study. This adhesive contains 65% fillers (moderately filled) which are a combination of silica and zirconia nanofiller and also involves dimethacrylate polymer that modifies the viscosity of the material and provides a flow-on demand handling characteristic allowing the material to flow under pressure.[19] Furthermore, this resin holds its shape after placement until light-cured.

Specimen preparation

For the *in vitro* study, 75 human premolars extracted for orthodontic purposes were obtained from patients aged 15–20 years. The exclusion criteria for the teeth were caries; any type of restoration; crack(s); erosion; fluorosis; and/or hypocalcification. All extracted teeth were cleansed of residual tissue, debris, calculus and were disinfected in 0.5% chloramine solution and stored in distilled water at room temperature until the study begin within 5 months.

Teeth were randomly divided to one of the three groups of 25 specimens: Group I (control group/direct bonding with a light-cured resin); Group II (indirect bonding with a chemically-cured resin); and

Group III (indirect bonding with a light-cured flowable resin) [Figure 1].

In vitro direct technique

In Group I, 25 teeth were placed in self-curing dental acrylic blocks using plastic molds. Tooth crowns were then cleaned with fluoride-free paste (Detartrine, Septodont, Saint-Maur-Des-Fosses, France) for 10 s with a low-speed rubber cup and rinsed for 30 s. The teeth were etched with 37% orthophosphoric acid gel (Etch Royale, Pulpdent Co, Watertown, Mass, USA) for 15 s, rinsed with air-water spray for 20 s, and air-dried with compressed air for 10 s. An adhesive primer (Transbond XT primer, 3M Unitek, Monrovia, CA, USA) was applied to the enamel. Stainless steel premolar brackets with 0.018-inch slot (Gemini Series, Low Profile, 3M Unitek, Monrovia, CA, USA) were attached to the enamel with a direct bonding light-cured resin (Transbond XT) and cured with a light-emitting diode (LED) light source (Elipar S10, 3M ESPE, St Paul, MN, USA) for 20 s per side (mesial and distal).

In vitro indirect technique

To simulate indirect bonding, 50 teeth were fixed in five upper acrylic dental models by sticky wax with 10 premolar teeth per model (5 in each quadrant); [Figure 2]. Alginate impressions (Cavex, Holland BV, Haarlem, Netherlands) were taken from the acrylic models and hard orthodontic stone (Snow White Stone, Heraeas Kulzer, Hanau, Germany) was poured into the impression immediately with a vacuum mixer. The casts were allowed to dry overnight and then isolated with a separating medium (Isolant, Dentsply, York, PA, USA) which was diluted with water at a 1:1 ratio and plaster models were set for 30 min to dry. Stainless steel premolar brackets with 0.018-inch slot (Gemini Series, Low Profile, 3M Unitek, Monrovia, CA, USA) were attached to the teeth in the plaster model with light-cured resin (Transbond XT, 3M Unitek, Monrovia, CA, USA) [Figure 3a]. Excess resin was removed with a scaler, and the remaining resin cured with a LED light for 40 s per side. This extended curing is necessary for the polymerization of the adhesive on the plaster models because the orthodontic stone and enamel have different transparency. After all the brackets were bonded to the plaster model, a transparent silicone impression material (Memosil 2, Heraeus Kulzer, Wehrheim, Germany) was used to fabricate the transfer trays [Figure 3b]. After hardening of the trays, plaster models were soaked into warm water for 20 min, and the trays were gently removed from the plaster models. The resin bases were sandblasted with 50-µm aluminum oxide particles (Danville Materials, San Ramon, Calif, USA) for 1 s, 2–10 mm distance then washed and dried with compressed oil-free air to remove residues of any contaminant.

The teeth on the acrylic dental models were cleaned with fluoride-free paste for 10 s using a low-speed rubber cup, washed for 30 s, dried, etched with 37% orthophosphoric acid gel for 15 s, rinsed with air-water for 10 s, and air-dried with compressed air for 10 s.

For Group II, a chemically-cured indirect bonding adhesive (Transbond IDB, 3M Unitek, Monrovia, CA, USA) was used in the left quadrant. Resin components part A and part B were mixed for 10 s and applied a thin coat of the mixed adhesive to both the teeth surface and the bracket bases on the transfer trays [Figure 4a]. The trays were pressed firmly with finger pressure onto the models for 3 min and left in place without any pressure for an additional 1 min according to the manufacturer's instructions [Figure 4b]. After the recommended polymerization time, the trays were divided into two parts with a lancet and removed with a scaler [Figure 5a and b].

For Group III, a light-cured flowable indirect bonding adhesive (Transbond Supreme LV, 3M Unitek, Monrovia, CA, USA) was used in the right quadrant of the same acrylic models. An adhesive primer (Transbond XT primer, 3M Unitek, Monrovia, CA, USA) was applied to the enamel, and the resin applied to the brackets on the trays with its proprietary syringe [Figure 6a]. The trays were pressed firmly onto the models with finger pressure and the resin cured with the LED light source (Elipar S10, 3M ESPE, St Paul, Minn, USA) for 20 s per side [Figure 6b]. The transfer trays were divided into two parts with a lancet and removed with a scaler after light cure polymerization [Figures 5a, b and 7].

Immediately after bonding, 50 teeth were removed from the acrylic dental model carefully and were placed in self-curing dental acrylic blocks using plastic molds [Figure 8a]. Different color of acrylic were used for the construction of different groups [Figure 8b].

All 75 teeth were placed into distilled water for 72 h and then subjected to SBS testing.

Shear bond strength testing

The brackets were debonded with a universal testing machine (Lloyd LRX, Lloyd Inst, UK) at a crosshead speed of 1 mm/min. A chisel-edge plunger was mounted in the movable crosshead of the universal testing machine and positioned at the tooth-bracket interface to allow the force could be parallel to the bracket base [Figure 9]. The maximum force required to debond the bracket was recorded in newtons (N) and converted to megapascals (MPa) by dividing the obtained value by the bracket surface area (9.61 mm^2).

Adhesive remnant index evaluation

As a final step, the enamel surfaces were inspected under a stereomicroscope (Zeiss, Opmi Pico F 170, Oberkochen, Germany) 10× magnification and an adhesive remnant index (ARI) was determined on a five-point scale, as follows.[20,21]

Score 1: The entire composite remained on the tooth, with an impression of the bracket base.

Score 2: More than 90% of the composite remained on the tooth.

Score 3: More than 10% but <90% of the composite remained on the tooth.

Score 4: Less than 10% of composite remained on the tooth surface.

Score 5: No composite remained on the enamel.

In vivo indirect technique

For the *in vivo* part of the study, twenty patients (range: 11 years, 11 months–17 years, 5 months) were selected according to the following inclusion criteria: (1) Angle Class I malocclusion; (2) nonextraction treatment only; (3) no caries, restorations, cracks, erosion, fluorosis, or hypocalcification; (4) complete permanent dentition; (5) no previous orthodontic treatment; (6) no skeletal discrepancy; (7) no cigarette smoking; and (8) no use of medication.

Patients were included only with their approval. Informed consent was obtained from all individual participants included in the study.

Laboratory stage

Initial records were produced. Alginate impressions (Cavex, Holland BV, Haarlem, The Netherlands) were taken from the patients and hard orthodontic stone (Snow White Stone, Heraeas Kulzer, Hanau, Germany) was poured into the impression immediately with a vacuum mixer. The casts were allowed to dry overnight and then isolated with a separating medium (Isolant, Dentsply, York, PA, USA) which was diluted with water at a 1:1 ratio, and plaster models were set for 30 min to dry. Bracket positioning guidelines were drawn according to panoramic radiograph.[22] Stainless steel brackets with 0.018-inch slot (Gemini Series, Low Profile, 3M Unitek, Monrovia, CA, USA) were attached to the teeth (including all of the first molars) in the plaster model with light-cured resin (Transbond XT, 3M Unitek, Monrovia, CA, USA) [Figure 3a]. Excess resin was removed with a scaler, and the remaining resin cured with a LED light for 40 s per side. This extended curing is necessary for the polymerization of the adhesive on the plaster models because the orthodontic stone and enamel have different transparency. A transparent silicone impression material (Memosil 2, Heraeus Kulzer, Wehrheim, Germany) was used to fabricate the transfer trays [Figure 3b]. After hardening of the trays, plaster models were soaked into warm water for 20 min, and the trays were gently removed from the plaster models. The resin bases were sandblasted with 50-μm aluminum oxide particles (Danville Materials, San Ramon, Calif, USA) for 1 s, 2–10 mm distance then washed and dried with compressed oil-free air to remove residues of any contaminant.

Clinical stage

Teeth of the patients were cleaned with fluoride-free paste (Detartrine, Septodont, Saint-Maur-Des-Fosses, France) for 10 s using a low-speed rubber cup, washed for 30 s, dried, etched with 37% orthophosphoric acid gel Etch Royale, Pulpdent Co, Watertown, Mass, USA) for 15 s, rinsed with air-water for 10 s, and air-dried with compressed air for 10 s.

A split-mouth design was used, whereby the upper left and lower right quadrants were bonded using chemically-cured indirect bonding adhesive (Transbond IDB, 3M Unitek, Monrovia, CA, USA), and the upper right and lower left quadrants were bonded using light-cured flowable indirect bonding adhesive (Transbond Supreme LV, 3M Unitek, Monrovia, CA, USA). These quadrants were rotated clockwise within each patient to eliminate interpatient and intrapatient differences.

For the *in vivo* study, teeth which were bonded with chemically-cured indirect bonding adhesive were in Group I and teeth which were bonded with light-cured flowable indirect bonding adhesive were in Group II [Figure 1].

Both maxillary and mandibular teeth including the first molars (total number: 462) were bonded. During indirect bonding, 11 teeth were excluded because of early bond failure. These failures were taken place during the removal of the transfer trays.

After bonding, the same archwire sequences were followed for all patients. Air-rotor stripping was used for eliminate the crowding if needed. Participants were reviewed every 4 weeks and the bracket failure rates monitored for 12 months.

Statistical analysis

SPSS (Statistical Package for Social Sciences, Windows 20.0, IBM Corporation, Armonk, New York, United States) and SAS (Statistical Analysis System, 9.0, SAS Institute, Cary, North Carolina, United States) software by a professional expert. The bond

strengths were compared using one-way analysis of variance (ANOVA), with Tukey's (honest significant difference) *post hoc* test. The mean differences were considered statistically significant at $P < 0.05$. A Weibull analysis was performed, where the Weibull modulus (the stress levels at 5% probability of failure and 10% probability of failure) was calculated. For the ARI scores, a Chi-square test (with Monte Carlo technique) was performed. In the *in vivo* study, Pearson Chi-square and Kruskal–Wallis tests were used to compare bond failure rates among the groups and anterior-posterior bracket failure rates.

Results

The mean SBS descriptive statistics and the results of the Weibull analysis are given in Table 1 and Figures 10 and 11 shows the Weibull distribution of the probability of failure at particular stress levels for each group. The highest bond strength was obtained for Group I (17.7 ± 6.2 MPa). The lowest bond strength was obtained for Group II, which was bonded indirectly using a chemically-cured resin (13.1 ± 4.8 MPa). The results of ANOVA demonstrated significant differences in SBS between the groups ($P < 0.05$), and Tukey's test confirmed that the SBS for Group II was significantly lower than for Group I. No other differences between the groups were detected ($P > 0.05$).

In the Weibull analysis, the lowest value was for Group II at the 5% probability of failure (5.3 MPa). The highest value was for Group I, at the 5% probability of failure (7.6 MPa). No statistically significant differences in ARI scores were found between the groups ($P > 0.05$) [Table 2 and Figure 12].

The average age of patients was 14 years, 5 months ± 2 years, 1 months (range: 11 years, 11 months–17 years, 5 months). *In vivo* bracket failure rates are given in Table 3. A total number of 462 brackets were bonded: 230 with chemically-cured resin and 232 with flowable light-cured resin. There were six failures in Group I (chemically-cured resin; 2.6%) and four failures in Group II (light-cured flowable resin; 1.7%). The total bracket failure rate was 2.16%. All failures occurred during the first 5 months of treatment [Table 3]. Pair-wise comparisons among the groups showed no significant differences between groups ($P > 0.05$), but when failures of the

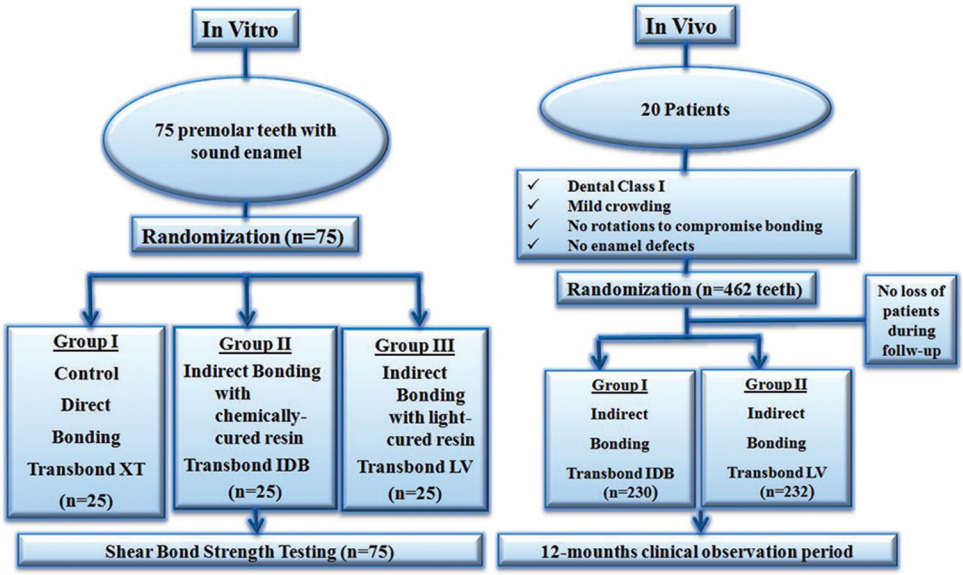

Figure 1: Flowchart of the study method

Table 1: Shear bond strength descriptive statistics and Weibull parameters

	Descriptive statistics				Weibull parameters		
	Mean (MPa)	Minimum	Maximum	SD	Weibull modulus	Stress at 5% probability of failure	Stress at 10% probability of failure
Group I	17.64	8.6	27.5	6.6	2.9	7.6	9.6
Group II	13.15	8	26	4.7	2.6	5.3	6.8
Group III	15.14	8.3	25.6	5.7	2.8	6.2	7.9

Group I=Direct (Transbond XT); Group II=Indirect chemically-cured (Transbond IDB); Group III=Indirect light-cured (Transbond LV); SD=Standard deviation

molar tubes were compared, rates were found to be higher in Group I (66.7%) than in Group II (50%). Six of the failed brackets were belong to 1st molar tubes (posterior/60%). One of the failed brackets was belong to maxillary central and all of the remaining were belonged to premolars (anterior/%40). Incisors and premolars were classified as anterior and molars were classified as the posterior segment. There was a significant difference for failed anterior and posterior brackets according to Kruskal–Wallis test ($P = 0.029$, $P < 0.05$). The failure rate for anterior brackets was higher for Group II (light-cured flowable resin). The failure rate for posterior brackets (1st molar) was higher for Group I (chemically-cured resin).

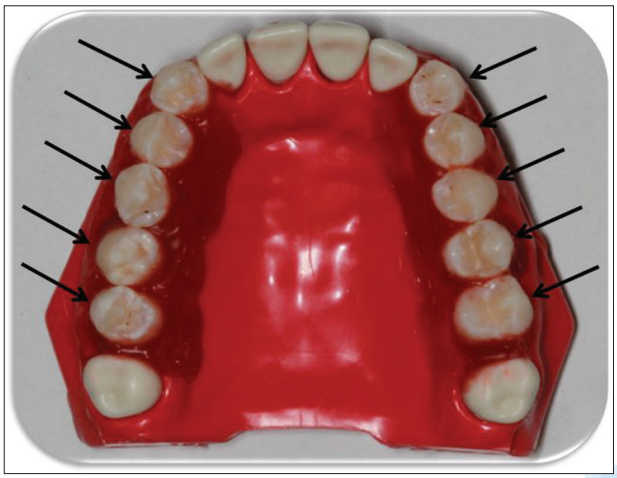

Figure 2: Illustration of premolar teeth in an acrylic dental model

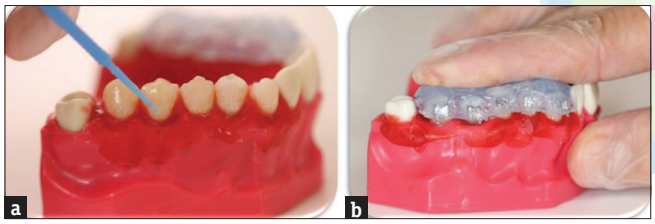

Figure 4: (a) Application of the chemically-cured adhesive to the teeth in Group II. (b) The transfer of the tray in Group II

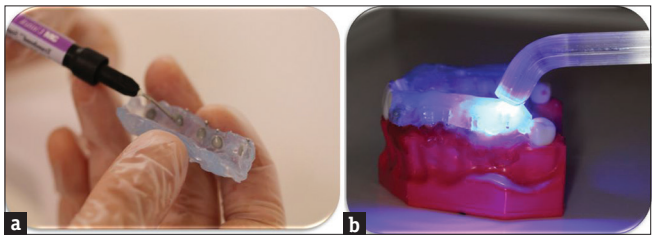

Figure 6: (a) Application of the light-cured flowable adhesive to the tray in Group III. (b) Curing of the resin with the LED source

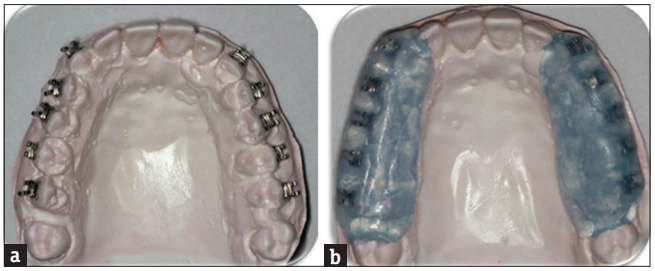

Figure 3: (a) Brackets were attached to stone model. (b) Transparent transfer tray

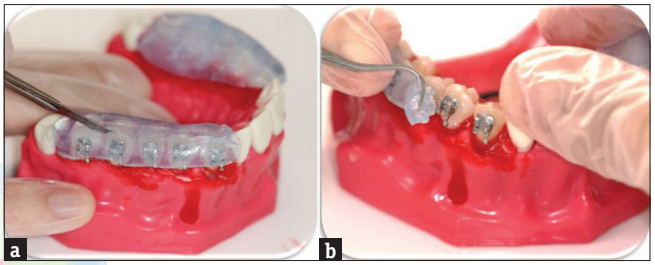

Figure 5: (a) After transfer, tray was cut with a lancet. (b) Transfer tray was removed with a scaler

Figure 7: Brackets, after the transfer on the acrylic dental model

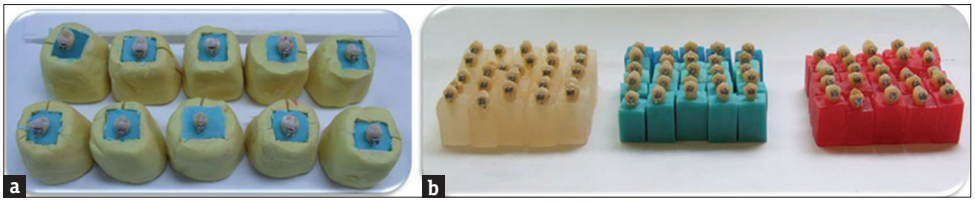

Figure 8: (a) Teeth in acrylic blocks. (b) Different color of acrylic were used for construction of different groups

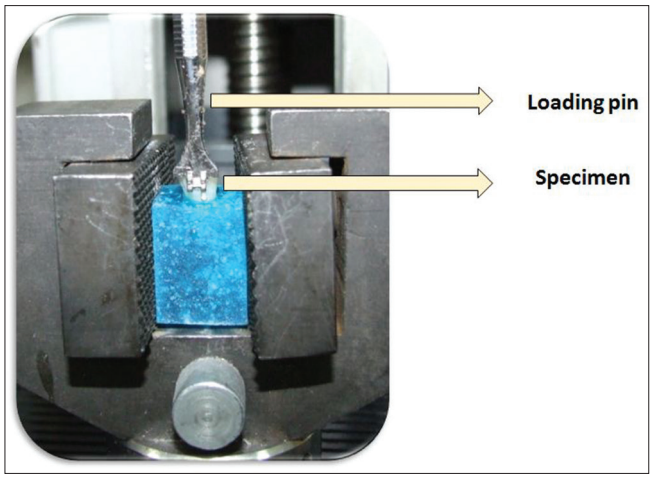

Figure 9: Specimen in the universal testing machine

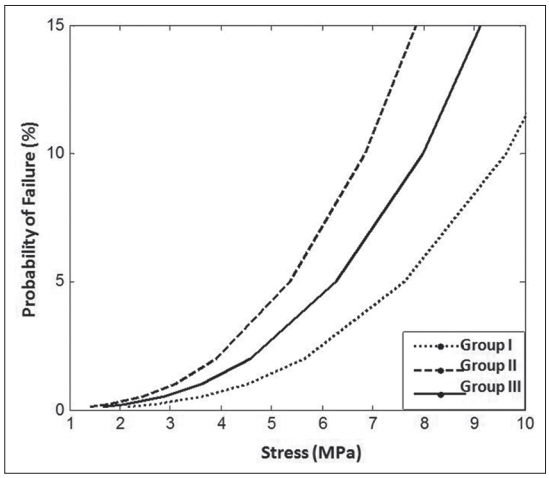

Figure 10: Weibull distributions of the groups at 0%–15% probability of failure. Groups: (I) Direct, Transbond XT; (II) Indirect, Transbond IDB; and (III) Indirect, Transbond LV

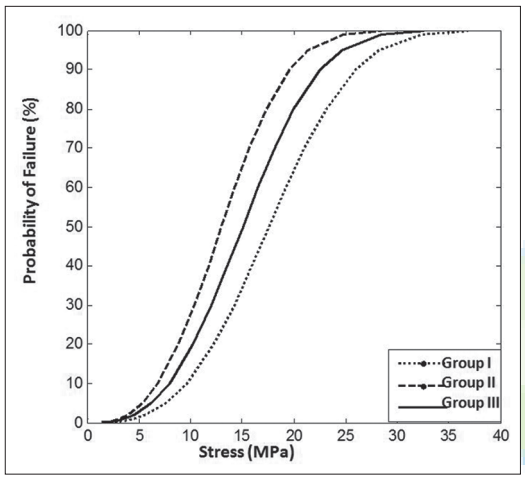

Figure 11: Weibull distributions of the groups at 0%–100% probability of failure. Groups: (I) Direct, Transbond XT; (II) Indirect, Transbond IDB; and (III) Indirect, Transbond LV

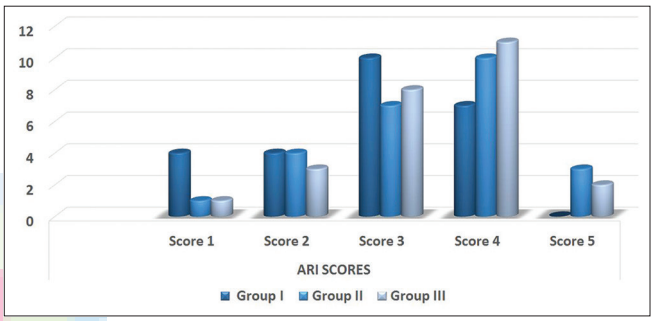

Figure 12: ARI scores of the groups. Groups: (I) Direct, Transbond XT; (II) Indirect, Transbond IDB; and (III) Indirect, Transbond LV

Table 2: Frequency distribution of adhesive remnant index scores of the groups

	ARI scores					Multiple comparison		
	1	2	3	4	5	Group I	Group II	Group III
Group I (*n*)	4	4	10	7	0		NS	NS
Group II (*n*)	1	4	7	10	3	NS		NS
Group III (*n*)	1	3	8	11	2	NS	NS	

Group I=Direct (Transbond XT); Group II=Indirect chemically-cured (Transbond IDB); Group III=Indirect light-cured (Transbond LV); NS=Not significant; ARI=Adhesive remnant index

Table 3: Bond failures *in vivo*

Group	*n*	Month											
		1	2	3	4	5	6	7	8	9	10	11	12
Group I	230	2	1	1	2	0	0	0	0	0	0	0	0
Group II	232	0	2	1	0	1	0	0	0	0	0	0	0

Group I=Indirect chemically-cured (Transbond IDB); Group II=Indirect light-cured (Transbond LV)

Discussion

In recent years, resins have been developed specifically for orthodontic indirect bonding.[11-14] One such product was a chemically-cured resin, but this failed to provide adequate SBS compared with direct bonding.[16] Yi *et al*. investigated SBS values for direct (adhesive precoated brackets) and indirect (chemically-cured indirect bonding resin) methods and found no statistically significant differences between the groups.[14] Klocke *et al*. compared SBS values for light-cured, chemically-cured, and thermal-cured adhesives in indirect bonding and found that chemically-cured indirect bonding resin (Sondhi Rapid Set) was comparable to the direct group, but that chemically-cured indirect bonding resin (Custom IQ) was inferior to both. Polat *et al*. compared similar systems and showed that one type of chemically-cured indirect bonding resin gave significantly lower SBS values than both a second chemically-cured indirect bonding resin (Custom IQ) and a direct bonding group.[11,13] Conversely, Linn *et al*. found no significant differences in SBS values when

comparing a chemically-cured indirect bonding resin and a light-cured adhesive (Enlight LV).[12] Hence, we had chosen a contemporary chemically-cured indirect bonding resin for comparing the SBS values to a direct bonding resin for this study.

In 2002, Miles used flowable light-cured resin for indirect bonding. Flowable resins have the advantage of filling the gaps between the customized resin base and the enamel, eliminating voids while providing adequate strength for indirect bonding.[23] For this reason, we had chosen a contemporary flowable light-cured adhesive as a second indirect bonding resin for this study.

In the literature, there is no other study which is comparing these two indirect bonding resins to each other and a direct bonding resin.

In the present study, *in vitro* Group II (chemically-cured indirect bonding) demonstrated the lowest SBS compared with the direct group, a difference likely attributable to the technical sensitivity required for achieving high bond strength with chemically-cured resins.[11,14] Even slight movements of the tray during polymerization may result in weakened bond strength. Our results are in accordance with the results of Polat *et al*., who also reported a difference between direct bonding and chemically-cured indirect bonding.[13] Chemically-cured resins are useful in indirect bonding where a non-transparent tray is used. In this circumstance, we would recommend the division of the tray into 2–3 pieces for maximum control during polymerization.

During orthodontic treatment, the brackets must withstand the forces of mastication. The basic method to simulate these forces is the evaluation of SBS. Reynolds submitted that the minimum bond strength of an orthodontic adhesive must be 5.9–7.8 MPa.[24] The mean SBS values of all groups in the present study were adequate according to Reynolds' threshold value.

However, the performance of adhesives in the *in vitro* studies cannot be directly extrapolated to *in vivo* situations. *In vitro* studies are conducted under idealized conditions that do not accurately reflect the oral environment.[25] Clinically, there is a risk of contamination by saliva and blood, erosion of the adhesive by foodstuff, and difficulty in reaching certain areas of the mouth. Highly detailed methods such as survival analysis may help in interpreting *in vitro* results and extracting clinically relevant conclusions from them.

Weibull analysis is a useful survival analysis method for evaluating the fracture behavior of materials and the probability of failure at a certain stress level.[26] This analysis also evaluates material imperfections (e.g., pores and defects) that can cause debonding. Even if a material has high mean bond strength, it may still debond at low-stress levels. The stress level (in MPa) at 5% probability of failure is important in indirect bonding. Klocke *et al*. suggested that this stress level is equivalent to the removal of the transfer tray during indirect bonding.[27] In their study, they found that the minimum stress level at 5% probability of failure is 3.3 MPa. In this study, the lowest stress level at 5% probability of failure is 5.36 MPa for the chemically-cured indirect bonding adhesive (Transbond IDB), well above the stress level determined by Klocke *et al*.

The Weibull modulus demonstrates the strength of a material, the homogeneity of the data, and the predictability of its clinical performance. If this modulus is high, the material is durable, the data are homogeneous and good clinical performance is expected. The highest Weibull modulus obtained in this study was for Group I (direct bonding with Transbond XT) and the second highest was for Group III (indirect bonding with Transbond LV).

ARI scores were generally 3 or 4, and no statistically significant differences were found between groups, demonstrating that fracture type was generally cohesive or a combination of adhesive and cohesive. The cohesive fracture type is more reliable than the adhesive fracture.[28]

All groups showed favorable ARI scores. Our findings were in agreement with several previous studies, where there were no differences between the direct and indirect bonding groups[8,13,29] but are contrary to several other studies that did report ARI score differences.[14,30]

As expected for the indirect bonding technique, the low-filled composite resin separates from the bracket, producing high ARI scores.[13] In direct bonding, the highly filled composite resin usually remains on the enamel, generating lower ARI scores, consistent with our data.[13] An ARI score of 5 indicates fracture of the enamel. This was never observed in the direct bonding group but was seen at rates of 12% and 8% in Groups II and III, respectively, suggesting the possibility of some degree of enamel loss after debonding of these adhesives.

A split-mouth design was used for the *in vivo* study to allow the chewing forces to be distributed equally between the different adhesive groups and to minimize the effect of personal differences such as brushing and eating habits.

To assess the clinical behavior of the indirect bonding adhesives, a 12-month clinical evaluation was also conducted. Both the chemically-cured (Transbond IDB) and light-cured resins (Transbond LV) showed similar

failure rates across the 12-month observation period. The limited period of clinical observation was a potential weakness of our study, because most orthodontic treatments last longer than this period and so may not be accurately simulated by this model. However, previous studies have concluded that bracket failures generally occur within the first 6 months of treatment, consistent with our observation that all bracket failures occurred within the first 5 months of treatment, suggesting that our model does cover the relevant period.[6] Nevertheless, longer observation periods are recommended for more reliable simulation of the clinical situation.

Cal-Neto *et al*. suggested that a clinical failure rate of <10% is clinically acceptable.[31] In this study, the failure rate was 2.16%, and in published literature ranges varies from 1.2% to 8.8% for indirect bonding.[32,33] This wide range in failure rates may be attributed to several factors such as differences in the adhesives used, observation periods, sample size, and numbers of teeth included. Most studies did not include the 1st molars as these are likely to fail early. Miles and Weyant included the 1st molars in their indirect bonding study, and recorded failure rates of 2.9% for the chemically-cured resin group and 2.4% for the flowable light-cured resin group, values that are comparable to those calculated in our study.[34]

In indirect bonding technique, when transfer tray is removed the posterior segments receive more negative forces than anterior segments, and this can be a cause for bracket failures at the beginning of the treatment. There are many direct bonding studies which were concluded that posterior teeth have higher failure rates than anterior teeth.[35-38] This can be due to isolation problems and limited field of view for posterior segments, anatomical difficulties encountered during the bonding procedure, and high chewing pressure for posterior segments.[39] Group II (light-cured flowable resin) had better results in posterior segments; this can be attributed to the better polymerization of resin by ultraviolet light. Furthermore, chemically-cured resin can be affected by the movements of the tray and the changes of clinicians' pressure. Microfractures which can be occurred during the chemical polymerization can reduce the bonding strength.[40]

Conclusions

- Our first null hypothesis was partly rejected; the SBS produced by indirect bonding chemically-cured resin (Transbond IDB) was slightly inferior to that for light-cured flowable indirect bonding resin (Transbond LV) and for direct bonding *in vitro*. However, light-cured flowable indirect bonding resin (Transbond LV) and direct bonding resin had similar SBS results
- Second, null hypothesis was accepted. The indirect bonding resins have adequate bond survival rates *in vivo*, and the failure rates of each indirect bonding resin were deemed adequate for clinical application.

Financial support and sponsorship

Baskent University Research Fund.

Conflicts of interest

There are no conflicts of interest.

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