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Bonding of orthodontic brackets to PMMA-based CAD-CAM materials for temporary restorations as a function of universal adhesives and mechanical surface treatment

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Abstract

The study was aimed at assessing shear bond strength and failure mode (Adhesive Remnant Index, ARI) of orthodontic brackets bonded to polymethylmethacrylate (PMMA) blocks for CAD-CAM fabrication of temporary restorations, following substrate chemical or mechanical treatment. Two types of PMMA blocks were tested: CAD-Temp (VITA) and Telio® CAD (Ivoclar-Vivadent). The substrate was roughened with 320-grit sandpaper, simulating a fine-grit diamond bur. Two universal adhesives, Scotchbond Universal Adhesive (3M ESPE) and Assure Plus (Reliance), and a conventional adhesive, Transbond XT Primer (3M Unitek), were used in combination with Transbond XT Paste (3M Unitek) to bond the brackets. Six experimental groups were formed: 1) CAD-Temp/Scotchbond Universal Adhesive/Transbond XT Paste; 2) CAD-Temp/Assure Plus/Transbond XT Paste; 3) CAD-Temp/Transbond XT Primer/Transbond XT Paste; 4) Telio® CAD/Scotchbond Universal Adhesive/Transbond XT Paste; 5) Telio® CAD/Assure Plus/Transbond XT Paste; 6) Telio® CAD/Transbond XT Primer/Transbond XT Paste. Shear bond strength and ARI were assessed. On 1 extra block for each PMMA-based material surfaces were roughened with 180-grit sandpaper, simulating a normal/medium-grit (100 μm) diamond bur, and brackets were bonded with Transbond XT Primer/Transbond XT Paste. Shear bond strengths and ARI scores were compared with those of groups 3, 6. CAD-Temp recorded significantly higher shear bond strengths than Telio® CAD. With the use of Transbond XT Primer significantly lower levels of adhesion were reached than after the application of Scotchbond Universal Adhesive or Assure Plus. Roughening with a more coarse bur resulted in a significant increase in adhesion. In conclusion, bracket bonding to CAD-CAM PMMA can be promoted by grinding the substrate with a normal/medium-grit bur or by coating the intact surface with universal adhesives. With the use of appropriate pretreatments, bracket adhesion to CAD-CAM PMMA temporary restorations can be enhanced to clinically satisfactory levels.

1. Introduction

The growing interest in both oral health and esthetic dentistry has increased the demand for adult orthodontic treatment [1-4]. In the context of multidisciplinary treatment, the orthodontist is often faced with the need to bond brackets to teeth restored with temporary crowns [2-5]. Several materials and techniques are currently available to the clinician for the fabrication of temporary restorations [2-8]. However, if the patient is undergoing orthodontic therapy as a part of interdisciplinary treatment, materials capable of providing satisfactory properties for an extended period of time are preferred. Particularly, in recent years highly cross-linked polymethylmethacrylate (PMMA) resin prefabricated blocks have been marketed for use in CAD/CAM systems [9-23]. As a result of industrial fabrication under standardized conditions, these CAD/CAM polymer materials exhibit improved mechanical and esthetic properties [19,21-23], rendering PMMA-based milled temporary restorations especially suitable when a longer clinical service is requested, such as in an interdisciplinary treatment strategy involving an orthodontic phase [9,11,12]. Nevertheless, the adhesive conditions offered to orthodontic bracket bonding by such a densely polymerized restorative substrate have not been investigated yet. Expectedly, the adhesion of a resin composite to highly cross-linked PMMA should benefit from a pretreatment of the restorative substrate that can be either chemical or mechanical.

Regarding chemical treatment, universal adhesives have been claimed to successfully adhere to different restorative substrates [24], as well as to dental tissues, and have recently been proposed for several applications in dentistry [25,26]. In an *in vitro* study Hellak et al. reported that the universal adhesive Scotchbond Universal Adhesive (3M ESPE, St. Paul, MN, USA) provided satisfactory retention of orthodontic brackets onto metal, porcelain and composite substrates [27]. Lately, Assure Plus (Reliance Orthodontic Products, Itasca, IL, USA,) a one-step universal primer allegedly able to effectively bond orthodontic brackets to all intraoral surfaces including restorative substrates, was launched onto the market [28-30]. According to recent research findings, the bond strength of this new material was tested on sound [28] and fluorosed [29] enamel, as well as on ceramic materials [30]. However, the potential for universal adhesives to bond orthodontic brackets onto polymer materials for CAD-CAM temporary restorations deserves investigation and this was the objective of the first part of the present study. Specifically, the first tested null hypothesis was that two marketed universal adhesives did not significantly differ from each other or from a conventional orthodontic adhesive in their ability to bond metal brackets onto two types of PMMA-based CAD-CAM blocks. Another issue worthy of evaluation is whether the adhesion to densely polymerized PMMA can be enhanced by mechanical roughening of the substrate. In a recent in vitro study Wiegand et al. measured the shear bond strength of a resin composite to different CAD/CAM polymer materials for the purpose of reparability [9]. In the absence of any surface pretreatment, significantly weaker adhesion was established than when silica coating/silanization, aluminum oxide sandblasting, and mechanical roughening simulating diamond bur abrasion, were performed [9]. However, the influence of mechanical pre-treatment of PMMA blocks on the adhesion of orthodontic brackets has not yet been assessed. This was the aim of the second part of the study. The second formulated null hypothesis was that roughening of the PMMA blocks surface with abrasives simulating a fine-grit or a normal/medium-grit diamond bur did not significantly change the adhesive conditions offered to orthodontic brackets. Throughout the whole study, the adhesive conditions were assessed by measuring the shear bond strength of bonded brackets, as well as the amount of adhesive left on the substrate after debonding.

2. Material and methods

2.1. Chemical treatment of the substrate with universal adhesives

Two types of PMMA-based blocks for use in CAD-CAM systems were tested: CAD-Temp (VITA Zahnfabrik, Bad Säckingen, Germany) and Telio® CAD (Ivoclar Vivadent AG, Schaan, Liechtenstein). The chemical composition of the two materials is reported in Table 1. The dimensions of the blocks were 15.5 x 19 x 39 mm and 15.4 x 19 x 39 mm for CAD-Temp and Telio® CAD respectively. Up to 4 brackets could be bonded and horizontally spaced on each longitudinal surface of the block (Fig. 1). Thus, all the brackets of each experimental group (N=10) were bonded to the same single block. According to the manufacturer's instructions for the use of universal adhesives on resinous substrates [31,32], the bonding surface of each block was roughened using wet 320-grit silicon carbide paper at 1.3 N for 8 s [9], simulating the action of a fine-grit (40 μm) diamond bur. After roughening, the bonding surface was cleansed with ethanol and dried with an oil-free air spray. The adhesives Scotchbond Universal Adhesive (3M ESPE, St. Paul, MN, USA), Assure Plus (Reliance Orthodontic Products, Itasca, IL, USA), and Transbond XT Primer (3M Unitek, Monrovia, CA, USA), all in combination with Transbond XT Paste (3M Unitek, Monrovia, CA, USA), were used to bond the brackets to either PMMA-based material. Transbond XT Primer is considered to be a standard adhesive in orthodontics and served as the control material. The chemical composition of the tested adhesives is reported in Table 2. Six experimental groups were formed: group 1 CAD-Temp/Scotchbond Universal Adhesive; group 2 CAD-Temp/Assure Plus; group 3 CAD-Temp/Transbond XT Primer; group 4 Telio® CAD /Scotchbond Universal Adhesive; group 5 Telio® CAD/Assure Plus; group 6 Telio® CAD/Transbond XT Primer. Sixty stainless steel brackets for upper incisors of the Victory Series (3M Unitek, Monrovia, CA, USA) were randomly selected and randomly assigned to the 6 experimental groups. The average bracket base surface area reported by the manufacturer was verified by measuring with a digital caliper (Mitutoyo, Miyazaki, Japan). The area of the 10 brackets chosen at random was recorded and the mean value of the measured areas was calculated to be 11.02 mm^2. In the bonding procedure the adhesive was applied to the substrate with a brush and air-thinned with a gentle stream of air. Photo.polymerization of the adhesives Assure Plus and Transbond XT Primer is not recommended by the respective manufacturers. Regarding Scotchbond Universal Adhesive, in the absence of any specific manufacturer's indication for its use in bracket bonding and with the intention to standardize the bonding procedure in all the experimental groups, it was decided to omit light-curing also of this adhesive. Nevertheless, the manufacturer of Scotchbond Universal Adhesive recommends avoiding light-curing also when using this adhesive for veneer luting [31]. Thereafter, a small amount of Transbond XT Paste was applied onto the bracket base, and the bracket was firmly seated on the substrate using a scaler instrument. Excess resin composite was removed from the bracket base periphery with the scaler, and light-curing was performed with an LED curing light (Ortholux Luminous, 3M Unitek, Monrovia, CA, USA; output 1600 mW/cm^2), positioning the tip for 12 s on the mesial and 12 s on the distal side of the bracket. All bracket placements were carried out by the same operator (GDB). Debonding forces were determined within 30 minutes from the time of bonding. This is the amount of time commonly elapsing before archwire ligation, that imparts the first functional stress to the just established adhesive bond [33-35]. For debonding, a steel rod with a flattened end was attached to the crosshead of a universal testing machine (Controls, Milano, Italy). Specimens were secured in the lower jaw of the machine so that the bonded bracket base was parallel to the shear force direction (Fig. 1). Specimens were stressed in the occlusal-gingival direction at a crosshead speed of 1 mm per minute. The load necessary to debond the bracket was recorded in Newtons and the bond strength was expressed in MegaPascals by dividing the load at failure in Newtons by the surface area of the bracket in mm^2. After debonding, the bracket bases and the enamel surfaces were examined under an optical microscope at 20X magnification. The Modified Adhesive Remnant Index (ARI) proposed by Ostby et al. [35] was used to assess the amount of adhesive left on the enamel surfaces. This index ranges from 0 to 5 and the scores are defined as follows:

Score 1) all of the adhesive remained on the tooth (Fig. 2A);

Score 2) more than 90% of the adhesive on the tooth (Fig. 2B);

Score 3) 10%-90% of the adhesive on the tooth (Fig. 2C);

Score 4) less than 10% of the adhesive on the tooth (Fig. 2D);

Score 5) no adhesive remained on the tooth (Fig. 2E).

2.2. Mechanical treatment of the substrate

In order to assess the influence on bracket adhesion of mechanical treatment of the substrate, on one extra block per PMMA-based material, the surfaces were roughened with a wet 180-grit silicon carbide paper at 1.3 N for 8 s [9], simulating the action of a normal/medium-grit (100 μm) diamond bur. The bonding surface was then cleaned with ethanol and dried with an oil-free air spray. Consequently, the control adhesive Transbond XT Primer was applied with a brush and air-thinned with a gentle stream of air. Using Transbond XT Paste in the same way as described above, brackets were bonded to the substrates, 10 on a CAD-Temp block (group 7) and 10 on a Telio® CAD block (group 8). Bracket debonding and ARI assessment were performed in the same way as in the protocol for testing the influence of chemical treatment. The collected data were compared with those of experimental group 6, that had been recorded on blocks roughened with a finer-grit silicon carbide paper.

3. Calculation

3.1. Shear bond strength

Having excluded through a linear regression that the PMMA block surface per se was an influential factor for the measured bond strengths, the bracket was considered as the statistical unit. Normality of data distribution (Kolmogorov-Smirnov test) and homogeneity of group variances (Levene test) were confirmed and then Two-Way Analysis of Variance (ANOVA) was applied with bond strength as the dependent variable, substrate and substrate treatment as factors. The Tukey test was utilized for post hoc comparisons as needed. In all the analyses the level of statistical significance was set at $p<0.05$.

3.2. ARI score

In order to assess the statistical significance of the between-group differences in the amount of adhesive left on the substrate, the Kruskal Wallis Non Parametric ANOVA test was applied to ARI scores, followed by the Dunn's Multiple Range test for post hoc comparisons. In all the tests the level of statistical significance was set at $p<0.05$.

4. Results

4.1. Chemical treatment of the substrate with universal adhesives - shear bond strength

The descriptive statistics of shear bond strength data are reported in Table 3. The Two-Way Analysis of Variance demonstrated that the type of polymeric material for CAD-CAM fabrication of temporary restorations had a significant influence on bracket adhesion per se ($p=0.02$). Particularly, CAD-Temp offered significantly more favorable bonding conditions than Telio® CAD. Also, the type of adhesive proved to be a significant factor for bracket retention ($p<0.001$). Specifically, with the use of Transbond XT Primer significantly weaker bonds were established than after the application of Scotchbond Universal Adhesive and Assure Plus ($p<0.05$), that achieved comparable levels of bond strengths ($p>0.05$). The substrate-adhesive interaction was not statistically significant ($p=0.311$).

4.2. Chemical treatment of the substrate with universal adhesives - ARI score

Descriptive statistics of ARI scores are presented in Table 4. The Kruskal Wallis non parametric test demonstrated statistically significant differences in ARI scores amongst the experimental groups ($p<0.001$). In particular, the Dunn's Multiple Range test disclosed that a significantly smaller amount of resin composite remained on the substrate in specimens that received Transbond XT Primer, in comparison with those treated with Scotchbond Universal Adhesive or in comparison with CAD-Temp blocks coated with Assure Plus ($p<0.05$).

4.3. Mechanical treatment of the substrate - shear bond strength

The descriptive statistics of shear bond strength data are reported in Table 5.

The Two-Way Analysis of Variance revealed that the type of polymeric material was not an influential factor for bracket adhesion per se ($p=0.686$). Regardless of the type of substrate, roughening with a coarser abrasive increased significantly bracket adhesion ($p<0.001$). Also, the substrate-abrasive interaction was statistically significant ($p=0.026$): both CAD-Temp and Telio® CAD had their retentive potential significantly enhanced by roughening with the coarser silicon carbide paper, reproducing a normal/medium grit diamond bur ($p<0.05$).

4.4. Mechanical treatment of the substrate – ARI score

The descriptive statistics of ARI scores are reported in Table 6. The Kruskal Wallis Non Parametric ANOVA test disclosed statistically significant differences in ARI scores amongst the experimental groups ($p<0.001$). In particular, the Dunn's Multiple Range test indicated that a significantly smaller amount of resin composite remained on the surfaces roughened with the finer abrasive ($p<0.05$).

5. Discussion

The study's outcome leads to rejection of both formulated null hypotheses.

Regarding the influence of chemical substrate treatment on bracket retention, the first interesting finding was that, regardless of the adhesive, CAD-Temp was more receptive to bonding than Telio® CAD. The difference between the two PMMA-based materials was not notable in absolute terms, though significant from a statistical point of view (Table 3). When considering the chemical composition of the two materials (Table 1), it is evident that CAD-Temp also contains some silica microfillers, while Telio® CAD is made almost completely of PMMA. It can be speculated that the silica filler of CAD-Temp contributed positively to adhesion. Nevertheless, this hypothesis would need further verification.

More remarkable was the effect of the universal adhesives. Coating the substrate with either Scotchbond Universal Adhesive or Assure Plus resulted in a significant increase in bracket bond strength, in comparison with the use of Transbond XT Primer (Table 3). Distinctive ingredients of the universal adhesives, compared with the conventional bonding system, are hydroxyethyl methacrylate (HEMA) and 10-methacryloyloxydecyl dihydrogenphosphate (10-MDP) (Table 2). While the role of these monomers in adhesion to enamel and dentin, as well as to zirconia has been clarified [24,25,36,37], no information could be retrieved in the literature about the mechanism by which the same monomers could promote adhesion to methacrylates. It can therefore only be expected that HEMA contributed by reducing the adhesive solution viscosity, in comparison with the bisphenol

A diglycidyl methacrylate (Bis-GMA) based adhesive Transbond XT Primer, while 10-MDP purportedly provided a chemical bond with the methacrylates of the substrate.

In a notable publication, Reynolds established 6-8 MPa to be the threshold of clinical acceptability for bracket bond strength [38]. With reference to these values, the adhesion levels recorded in most experimental groups in the present study would appear poor. However, the authors of a systematic review and meta-analysis on *in vitro* orthodontic bond strength testing [39], questioned the use of the threshold values proposed by Reynolds, by reporting that it has never actually been tested whether 6-8 MPa is a sufficient *in vitro* bond strength for clinical use [40,41]. Still on this issue, Eliades et al. [42] warned against the risks of extrapolating from absolute bond strength values and relating them with a supposedly 'clinically acceptable' limit. In fact, the bond strengths measured in a test are related to the peculiar experimental conditions of the trial and do not exactly apply to another testing environment.

In this perspective, with reference to a previous *in vitro* study following the same protocol and using the same testing equipment as in the present investigation [43], it is interesting to note that, after treatment of the PMMA surface with the universal adhesives, the achieved bracket bond strengths were similar to those established on enamel by a self-etch adhesive with proven satisfactory clinical performance [44]. Expectedly, in the absence of any pretreatment of the PMMA substrate, the levels of adhesion reached by Transbond XT Primer were lower than those recorded by this same adhesive on etched enamel in the mentioned previous study with the same design [43]. The two universal adhesives proved comparably effective at enhancing bracket adhesion to the PMMA-based materials.

Assure Plus was recently introduced in the orthodontic market as an 'all surface bonding resin', claimed to be able to increase bracket retention to all the dental hard tissues, including teeth with fluorosis or deciduous enamel and cement, as well as to restorative substrates of metallic, ceramic and polymeric nature [28-30,32]. Scotchbond Universal Adhesive has long been available to dental clinicians for several uses [24,25]. Mainly utilized in general dentistry for the bonding of direct and the luting of indirect restorations, Scotchbond Universal Adhesive was recently satisfactorily tested as a bracket bonding agent [26,27]. In this regard, as already pointed out by Hellak et al. [26,27], the choice of this material also by the orthodontist may be convenient in terms of office inventory costs. In other words, it is useful to know that Scotchbond Universal Adhesive, possibly already in use in the office for its various applications in restorative dentistry, can also be safely employed for 'all surface' bonding in orthodontics, thereby eliminating any need to stock an alternative material for this purpose.

Regarding ARI score evaluation, the observations were in line with the results of the bond strength tests. Lower bond strengths expectedly were seen with reduced retained adhesive on the substrate. A relevant finding was that in the totality of the specimens treated with the control, adhesive failure occurred at the interface between composite resin and substrate (Table 4), confirming that PMMA surfaces, if left untreated, offer poor conditions for bonding.

Mechanical pretreatment has traditionally been advised to increase bracket retention to polymer-based restorations, from composite fillings to provisional crowns [2-8]. It therefore seemed worthy to verify how surface roughening would affect adhesion to the new PMMA blocks for CAD-CAM temporary restorations. It was evident from the collected data that higher bond strengths were obtained by roughening PMMA surfaces with an abrasive replicating a normal/medium diamond bur (Table 5). Interestingly, the adhesion levels reached through roughening with the coarser abrasive were about the same as those obtained by pretreatment with the universal adhesives. As a clinical indication, it can therefore be inferred that the adhesion of orthodontic brackets to PMMA-based substrates can be equivalently enhanced by grinding with a normal/medium diamond bur or by coating the intact surface with a universal adhesive such as Scotchbond Universal Adhesive or Assure Plus.

The bond strength data corresponded well with ARI scores. The surfaces roughened with the coarser abrasive retained various amounts of bonding material, while the specimens which were more finely abraded, appeared free of any adhesive remnant after debonding (Table 6).

In this regard, it is also worth mentioning that, being provisional restorations designed for limited service, the possibility that grinding with a normal/medium bur may affect the superficial aspect of the crown is not a clinically relevant concern. In any case, even if the need to keep the provisional restoration beyond the end of orthodontic treatment should arise, the bur-roughened area previously covered by the bracket could easily be polished for better esthetics.

6. Conclusions

Based on the outcome of the present investigation, it can be concluded that the adhesion of orthodontic brackets to currently marketed PMMA-based CAD-CAM materials for temporary restorations can be enhanced to reach levels compatible with the clinical service by first grinding the substrate with a normal/medium-grit bur or by coating the intact surface with contemporary universal adhesives. The new CAD-CAM materials, which current prosthodontists may prefer due to their favorable mechanical and esthetic properties, can thus be safely used when the overall treatment strategy also involves an orthodontic phase with fixed appliances.

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Table 1. Chemical composition of the tested PMMA blocks.

	Manufacturer	Chemical composition
CAD-Temp	VITA Zahnfabrik, Bad Säckingen, Germany	83-86% wt.% PMMA, 14% wt% microfiller (silica), pigments (<0.1%)
Telio® CAD	Ivoclar Vivadent, Schaan, Liechtenstein	99.5% wt.% PMMA, no fillers, pigments (<0.1%)

Table 2. Chemical composition of the tested adhesives.

	Manufacturer	**Chemical composition**
Scotchbond Universal Adhesive	3M ESPE, St. Paul, MN, USA	10-MDP phosphate monomer, Vitrebond copolymer, HEMA, Bis-GMA, dimethacrylate resins filler, silane, initiators, ethanol, water
Assure Plus	Reliance Orthodontic Products, Itasca, IL, USA	Bis-GMA, ethanol, MDP, HEMA
Transbond XT Primer	3M Unitek, Monrovia, CA, USA	Bis-GMA, TEGDMA, 4-(dimethylamino)-benzeneethanol, camphorquinone, hydroquinone
Transbond XT Paste	3M Unitek, Monrovia, CA, USA	Silane treated quartz (70-80% in weight), bisphenol A diglycidyl ether dimethacrylate, bisphenol A bis(2-hydroxyethyl ether) dimethacrylate, silane treated silica, diphenyliodonium

Table 3. Descriptive statistics of shear bond strength data following chemical treatment of the substrate. The different capital superscript letters demonstrate a statistically significant difference in the bond strengths provided by the two PMMA-based materials, regardless of the adhesive used ($p<0.05$). The different small superscript letters show the statistically significant differences in the bond strength achieved by the adhesives, irrespective of the substrate ($p<0.001$).

PMMA-based material	Adhesive	N	Mean (MPa)	Standard Deviation
CAD-Temp^{A}	*Scotchbond Universal Adhesive*	10	7.51	1.40
	Assure Plus	10	8.15	1.89
	Transbond XT Primer	10	5.95	1.37
	Total	30	7.20	1.78
Telio CAD^{B}	*Scotchbond Universal Adhesive*	10	7.28	1.21
	Assure Plus	10	6.66	1.58
	Transbond XT Primer	10	5.23	1.10
	Total	30	6.39	1.59
Total	***Scotchbond Universal Adhesive**^{a}*	20	7.40	1.21
	***Assure Plus**^{a}*	20	7.41	1.58
	***Transbond XT Primer**^{b}*	20	5.59	1.26

Table 4. Descriptive statistics of ARI scores. In the significance column the different letters label the statistically significant differences amongst the experimental groups.

Group	N	Median	Interquartile range (25%-75%)	Significance p<0.05
CAD-Temp / Scotchbond Universal Adhesive	10	3	1-3	A
CAD-Temp / Assure Plus	10	3	3-3	A
CAD-Temp / Transbond XT Primer	10	5	5-5	B
Telio CAD / Scotchbond Universal Adhesive	10	3	1-3	A
Telio CAD / Assure Plus	10	3	3-5	AB
Telio CAD / Transbond XT Primer	10	5	5-5	B

Table 5. Descriptive statistics of shear bond strength data following mechanical treatment of the substrate. The different superscript letters demonstrate a statistically significant difference in the bonding conditions obtained by roughening with the two abrasives, regardless of the type of PMMA-based material ($p<0.001$)

PMMA-based material	Abrasive	N	Mean (MPa)	Standard Deviation
CAD-Temp	320 Grit[b]	10	5.95	1.37
	180 Grit[a]	10	7.98	1.21
	Total	20	6.96	1.63
Telio CAD	320 Grit[b]	10	5.23	1.10
	180 Grit[a]	10	8.99	0.95
	Total	20	7.11	2.17
Total	320 Grit[B]	20	5.59	1.26
	180 Grit[A]	20	8,48	1,18

Table 6. Descriptive statistics of ARI scores. In the significance column, the different letters label the statistically significant differences amongst the experimental groups.

Group	N	Median	Interquartile range (25%-75%)	Significance p<0.05
CAD-Temp / 320 grit	10	5	5-5	B
CAD-Temp / 180 grit	10	3	3-4	A
Telio CAD / 320 grit	10	5	5-5	B
Telio CAD / 180 grit	10	3	3-4	A

Fig. 1. The experimental set-up for bracket shear bond strength testing

Fig. 2. Optical microscope images of the PMMA substrate after bracket debonding (magnification X20). Figures A-E are respectively representative of 1-5 Adhesive Remnant Index (ARI) scores

A. ARI score 1	B. ARI score 2	C. ARI score 3	D. ARI score 4	E. ARI score 5