Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.intl.elsevierhealth.com/journals/dema

Bond strength tests of dental adhesive systems and their correlation with clinical results – A meta-analysis

Siegward D. Heintze[a,*], *Valentin Rousson*[b], *Eduardo Mahn*[c]

[a] *R&D, Ivoclar Vivadent AG, Schaan, Liechtenstein*
[b] *Biostatistics Unit, Institute for Social and Preventive Medicine, University of Lausanne, Switzerland*
[c] *Research Department, Universidad de los Andes, Santiago, Chile*

ARTICLE INFO

Article history:
Received 21 August 2013
Received in revised form
4 April 2014
Accepted 19 January 2015

Keywords:
Bond strength
Microtensile
Tensile
Macroshear
Meta-analysis
Class V
Clinical relevance

ABSTRACT

Objective. To evaluate the variability of bond strength test results of adhesive systems (AS) and to correlate the results with clinical parameters of clinical studies investigating cervical restorations.

Materials and methods. Regarding the clinical studies, the internal database which had previously been used for a meta-analysis on cervical restorations was updated with clinical studies published between 2008 and 2012 by searching the PubMed and SCOPUS databases. PubMed and the International Association for Dental Research abstracts online were searched for laboratory studies on microtensile, macrotensile and macroshear bond strength tests. The inclusion criteria were (1) dentin, (2) testing of at least four adhesive systems, (3) same diameter of composite and (4) 24 h of water storage prior to testing. The clinical outcome variables were retention loss, marginal discoloration, detectable margins, and a clinical index comprising the three parameters by weighing them. Linear mixed models which included a random study effect were calculated for both, the laboratory and the clinical studies. The variability was assessed by calculating a ratio of variances, dividing the variance among the estimated bonding effects obtained in the linear mixed models by the sum of all variance components estimated in these models.

Results. Thirty-two laboratory studies fulfilled the inclusion criteria comprising 183 experiments. Of those, 86 used the microtensile test evaluating 22 adhesive systems (AS). Twenty-seven used the macrotensile test with 17 AS, and 70 used the macroshear test with 24 AS. For 28 AS the results from clinical studies were available. Microtensile and macrotensile (Spearman rho = 0.66, $p = 0.007$) were moderately correlated and also microtensile and macroshear (Spearman rho = 0.51, $p = 0.03$) but not macroshear and macrotensile (Spearman rho = 0.34, $p = 0.22$). The effect of the adhesive system was significant for microtensile and macroshear ($p < 0.001$) but not for macrotensile. The effect of the adhesive system could explain 36% of the variability of the microtensile test, 27% of the macrotensile and 33% of the macroshear test. For the clinical trials, about 49% of the variability of retained restorations could be explained by the adhesive system. With respect to the correlation between bond strength tests and clinical parameters, only a moderate correlation between micro- and macrotensile test results and marginal discoloration was demonstrated. However, no

* *Corresponding author at*: Ivoclar Vivadent, Bendererstr. 2, 9494 Schaan, Liechtenstein. Tel.: +423 235 3570; fax: +423 233 1279.
E-mail address: siegward.heintze@ivoclarvivadent.com (S.D. Heintze).

http://dx.doi.org/10.1016/j.dental.2015.01.011

correlation between these tests and a retention loss or marginal integrity was shown. The correlation improved when more studies were included compared to assessing only one study.

Significance. The high variability of bond strength test results highlights the need to establish individual acceptance levels for a given test institute. The weak correlation of bond-strength test results with clinical parameters leads to the conclusion that one should not rely solely on bond strength tests to predict the clinical performance of an adhesive system but one should conduct other laboratory tests like tests on the marginal adaptation of fillings in extracted teeth and the retention loss of restorations in non-retentive cavities after artificial aging.

1. Introduction

In restorative dentistry, the largest area exposed after preparation is in most cases dentin. Therefore, bond strength on dentin is decisive for the restoration to be held in place. This is especially critical for those cavities/preparations with no or little mechanical retention like cervical restorations, crown stumps with reduced stump height and/or a high angle of convergence and overlay preparations. The sealing of the dentinal tubules is another important function of adhesive systems.

The effectiveness of an adhesive system to bond to dentin is commonly tested with a bond strength test. The first article on bond strength tests (tensile bond strength test) for dental materials was published in 1965 by Bowen [1]. Since then, many more articles have been published. Today, 4960 articles are listed in PubMed when searching for “bond strength” and “dental”, 2695 articles for “bond strength” and “dentin” as well as 1545 articles with the search terms “bond strength” and “enamel” (search period 1955–2012, search month November 2012). A further 3716 abstracts were retrieved from International Association for Dental Research (IADR) abstracts online (www.iadr.org, 2002–2012, search month November 2012, search term “bond strength” and “dentin”). These articles and abstracts advocate various test setups, such as the shear bond, microtensile, microshear, push-out and the fracture toughness test. There is only a small degree of standardization. Of the 4960 articles, only 12 relevant reviews critically evaluated the different bond strength tests in terms of their strengths and weaknesses [2–13]. The remaining large number of studies on bond strength testing in dentistry investigated various modifications of test setups and substrates. Additionally, most of them focused on testing specific materials.

Only after 30 years of bond strength testing, efforts were made to relate the results of these tests to clinical findings and to look at the variability of test results. Even now, only few publications exist which correlate the in vitro bond strength data with the clinical outcome of the tested adhesive systems. The clinical model most often used to test the effectiveness of adhesive systems is the restoration of non-carious cervical defects. Such defects are especially suitable to test adhesive systems due to the following: (1) practically no macro-mechanical retention is present, (2) straightforward clinical placement of the restoration and evaluation of debonding, reducing operator and evaluator variability, and (3) high prevalence, which makes patient selection simple and allows for properly designed studies. Only three publications on the correlation between bond strength tests and the clinical performance of restorations placed with adhesive systems have been published so far. In one of these studies [14], the microtensile bond strength data of 15 adhesive/restorative systems placed by the same operator were correlated with the clinical studies of non-carious cervical Class V restorations. No correlation was found between the retention rate of cervical restorations after 3 years and the microtensile test results after 8 h or 6 months of water storage of specimens prior to testing. There was, however, a very moderate correlation between marginal staining and bond strength values after 6 months of water storage. A comprehensive database of microtensile bond strength data and an equally comprehensive database on the retention rates of clinical restorations placed in non-carious wedge-shaped defects at the same test institute (University of Leuven) found a moderate correlation between bond strength of artificially aged specimens and clinical retention. The correlation was higher for the 5-year data than for the 2-year data [15]. However, most of product-related individual data – both clinical and laboratory – have not been published by that research group. Another attempt was made to correlate the bond strength data with the retention of cervical restorations. In 2010, Scherrer et al. [10] published data of laboratory studies on six dentin adhesive systems, available in the literature, and four laboratory methods (macroshear, microshear, macrotensile and microtensile bond strength test). The review revealed a large variability for the same adhesive system evaluated with the same bond strength method, not only at different test institutes (inter-institute variability) but also at the same test institute (intra-institute variability). The variability was similar for each test method. Scherrer and colleagues pooled the data across the different studies in relation to the adhesive system and the bond strength test and calculated mean values and standard deviations. These data were correlated with estimated pooled 2-year retention rates of Class V restorations using the same adhesive systems and retrieved from the databank of the meta-analysis on cervical restorations [16]. The results of the regression analysis for the pooled data demonstrated that only the macrotensile and microtensile tests but not the shear and the microshear tests correlated more accurately with the retention rate of cervical restorations. This finding allowed for

two hypotheses: (1) tensile tests correlate with the retention loss of cervical restorations whereas the shear tests do not. (2) Pooled data across different institutes may correlate more accurately with retention loss of cervical fillings than individual data from one test institute. The explanation may be that these pooled data characterize the variability and efficacy of a certain adhesive system more appropriately.

These assumptions, however, are only based on six adhesive systems and the selection criteria of the laboratory studies were not very restrictive and included studies with one adhesive system only, with specimens submitted to thermocycling, different bonding areas, etc.

The aims of the present meta-analysis were threefold:

1. To investigate the variability of bond strength tests on dentin by retrieving literature data on the three most commonly used tests: microtensile, macrotensile and macroshear. Furthermore, the correlation between these three tests should be assessed.
2. To investigate the correlation between these tests and clinical parameters from studies on cervical restorations (retention, marginal discoloration, marginal integrity).
3. To investigate whether the correlation improves if pooled data from different studies are used instead of data from single studies.

The following null hypotheses were formulated:

1. There is no correlation between the three test methods.
2. There is no correlation between bond strength tests and the clinical outcome of cervical restorations.
3. The pooling of data does not improve the correlation.

2. Materials and methods

2.1. Selection of in vivo studies

For the clinical performance of the different adhesive systems, results from prospective studies on cervical restorations (Class V) were retrieved from literature. The internal database used for the meta-analysis on Class V restorations and published in Dental Materials in 2010 [16] was updated with studies that were published between 2008 and 2012, using the same criteria as described in the publication, the same databases (PubMed and SCOPUS) and the same search words. The search period ranged from 2008 to 2012 and the search month was July 2012. However, for the in vitro/in vivo comparison only those studies with specific adhesive systems were used for which also in vitro data were available.

2.2. Selection of in vitro studies

For in vitro studies on bond strength, only studies that tested at least four different adhesive systems were included. The rationale was (1) that a reasonable ranking of adhesive systems in relation to the study should be possible, and (2) to simplify the literature search. However, there was no restriction with regard to the publication year. Other inclusion criteria were as follows:

- Human teeth.
- Mid-coronal dentin.
- Same diameter (macroshear, macrotensile) or diagonal (microtensile) of test specimen in relation to test method.
- 24 h of storage in water before conduction of bond strength test.

The databases PubMed (1955–2012) and IADR abstracts online (2002–2012) were searched using the following search terms: "bond strength" and "dentin". The search month was July 2012. The search focused on the microtensile (Test 1), macrotensile (Test 2) and macroshear tests (Test 3).

The following data were retrieved from the studies:

- Adhesive system (AS).
- Mean bond strength value (MPa).
- Standard deviation.
- Number of specimens and/or teeth used per group.

2.3. Modeling of in vivo performance

The clinical performance was measured by means of the percentage of retention loss (R), the percentage of marginal discoloration (MD) and the percentage of detectable margins (MI). Although the percentage of secondary caries or caries at the restorative margins was also measured, it was not considered in this analysis as most experiments had 0% of marginal caries. In correspondence with the previous study by Heintze et al. [16], a clinical index defined as $CI = (4R + 2MD + MI)/7$ was calculated in order to summarize the clinical performance by weighing the three most commonly reported clinical parameters and giving higher importance to retention than to marginal discoloration and marginal integrity. In what follows, all these percentage values are expressed such that they are equal to 100% at baseline and decreasing afterwards. They were assessed after 0.5, 1, 1.5, 2, 3, 4, 5, 6, 7, 8 and 13 years (depending on the studies). Since measurement results after 13 years were only available for 3 experiments (from the same study), and since there was a gap of 5 years between 8 and 13 years, we restricted our attention in what follows to the first 8 years of follow-up.

Since a linear deterioration over time may imply a percentage below 0, which is by definition not possible, we are considering the following model:

$$\frac{Y}{100} = \exp(-\lambda \times T^{\alpha} \times \text{error})$$

In this model, the percentage Y also decreases over time, but not linearly so that the percentage value remains above 0 (as long as λ is positive). This model is equivalent to the following linear model:

$$\log(-\log(Y/100)) = \beta + \alpha \times \log(T) + \text{error}$$

with $\beta = \log(\lambda)$.

In this model, the parameter β summarizes the deterioration occurring in an experiment. The deterioration depends on the fixed characteristics of the experiment, i.e. the factors adhesive, preparation (no/yes/missing), beveling (no/yes/missing) and rubber dam (no/yes/missing). To account for the fact that partly the same patients were assessed in

the different experiments of the same study, a random study effect was included in the model. Furthermore, to answer the correlations between the different measurements made in the same experiment, a random experiment effect was included. This results in a linear mixed effect model with the following variable value:

$$\beta = \text{reference value} + \text{effect of adhesive system} + \text{preparation effect} + \text{beveling effect} + \text{rubber dam effect} + \text{study random effect} + \text{experiment random effect}$$

The two random effects as well as the error term were assumed to be normally distributed. The reference value refers to the adhesive system No 2 (AdheSE) without preparation, without beveling and without rubber dam (in an average experiment from an average study). This reference value is thus a summary measure of the deterioration, i.e. of the in vitro performance of this adhesive. To get a summary measure of the in vitro performance of the other adhesives, the coefficients corresponding to the different adhesives estimated in our model may be added to this reference value. To fit a linear mixed effect model, we used the *lme* routine from the package *nlme*, implemented in the free statistical package package R. Using this routine, it was possible to weigh a percentage Y according to the denominator used for its calculation, i.e. the number of subjects available at a given point in time. Thus, the percentages calculated from many subjects received a higher weight than the percentages calculated from few patients.

2.4. Modeling in vitro performance

Similar to the in vivo experiments, we summarized the in vitro performance of the different adhesives. To do so, we used the coefficients corresponding to the effect of the adhesive system in a linear mixed model for the average performances calculated in the different experiments, a fixed effect of the adhesive system and a random study effect. Thus, we modeled the measurements Y, provided by the test methods, using the linear model: $Y = \beta + \text{error}$ where: β = reference value + effect of the adhesive system + study random effect. Since the measurements provided by the three test methods (in N/mm^2) do not share the same range (being much higher for Test 1 than for Test 2 and Test 3), this was done separately for each of the three test methods.

2.5. Correlation between clinical and in vitro performance

Using the coefficients corresponding to the effect of the adhesive system estimated in a linear mixed model as explained in the last two sections, it was possible to examine the correlation between the clinical and the in vitro performance of the different adhesives. Spearman correlations rho were calculated between the four measures of clinical performance (R, MD, MI, CI) and the three measures of in vitro performance.

2.6. Comparison of variability

It is not an obvious procedure to compare the variability of the estimates of clinical and in vitro performances as they are measured in different units. The in vitro performance is measured in Megapascal, whereas we summarized the clinical performance by means of a slope of deterioration for a percentage of clinical outcome parameters observed in a set of patients over time. To make such a comparison feasible, one possibility would be to calculate a ratio of variances, dividing the variance among the estimated effect of the adhesive systems obtained in our linear mixed models by the sum of all variance components estimated in these models.

For the in vitro performance the formula would be as follows:

$$\text{percentage of variance due to adhesive} = \frac{\text{variance(effect of adhesive system)}}{\text{variance(effect of adhesive system)} + \text{variance(study random effect)} + \text{variance(error)}.}$$

For in vivo performance, considering experiments with 50 patients, the formula would be

$$\text{percentage of variance due to adhesive} = \frac{\text{variance(effect of adhesive system)}}{(\text{variance(effect of adhesive system)} + \text{variance(study random effect)} + \text{variance(experiment random effect)} + \text{variance(error)}/50).}$$

3. Results

Thirty-two laboratory studies fulfilled the inclusion criteria and were included in the present analysis (Table 1). One of these studies tested the adhesive systems with both the tensile and microtensile test method [17]. Also one study was included that evaluated microtensile bond strength 8 h after water storage [14]. As it was not regarded as very important as to whether 8 h or 24 h were considered before testing and as the results of 7 adhesive systems could be used for comparison, this study has been included. These 32 studies comprised 183 experiments, 86 used Test 1, 27 used Test 2 and 70 used Test 3. The in vitro experiments tested 28 adhesive systems. Not each AS was tested by each test method. Data of 22 AS for Test 1, 17 AS for Test 2 and 24 AS for Test 3 were available. Only 14 AS (No 2, 6, 8, 11, 20, 22, 23, 24, 27, 30, 31, 37, 42 and 45) were tested using all three methods. The data consist of an average performance, such that the higher the average, the better the performance, calculated over a certain number of

Table 1 – Adhesive systems (AS) included in the present study. The numbers refer to those that appear in Figs. 1–5.

Number	Adhesive system	Adhesive class	Studies included
2	AdheSE	2-step selfetch	[1–8]
42	Adper Prompt L-Pop	1-step selfetch	[1,3–7,9–15]
4	All Bond 2	3-step etch and rinse	[16–19]
6	Clearfil Liner Bond 2	2-step etch and rinse	[17,18,20,21]
7	Clearfil Protect Bond	2-step selfetch	[2,7]
8	Clearfil SE Bond	2-step selfetch	[1–7,9,10,13–15,20,22–27]
47	Clearfil Tri-S Bond	1-step selfetch	[2,7,10–12,23,26,28]
11	Excite	2-step etch and rinse	[1,8,14,24,25,29,30]
15	Futurabond NR	1-step selfetch	[12]
50	G-Bond	1-step selfetch	[2,7,10–12,23,26,28,31]
19	Hybrid Bond	1-step selfetch	[7,11,12,28,31]
20	iBond	1-step selfetch	[1,3,6,8–13,28]
21	One Coat Bond	2-step etch and rinse	[21,25]
22	One Step	2-step etch and rinse	[16–18,20,22]
53	One Step Plus	2-step etch and rinse	[13,25,27]
45	One-up Bond	1-step selfetch	[6,8,11,13,14,31]
23	OptiBond FL	3-step etch and rinse	[2–5,9,11,14,15,21,29]
24	OptiBond Solo	2-step selfetch	[3,5,21,23]
25	PermaQuick	3-step etch and rinse	[16]
26	Prime & Bond 2.1	2-step etch and rinse	[22]
27	Prime & Bond NT	2-step etch and rinse	[1,5,8,13,20,21,24–26,30]
29	Prompt L-Pop	1-step selfetch	[8,20,25]
41	Scotchbond 2	2-step etch and rinse	[19,32]
31	Scotchbond Multipurpose	3-step etch and rinse	[6,9,16–20,27,29,32]
30	Single Bond/Scotchbond 1	2-step etch and rinse	[6,10,14,15,20,22,24,25,27,29,30]
32	Syntac Classic	3-step etch and rinse	[19,29,32]
34	Tenure	2-step etch and rinse	[32]
37	Xeno III	1-step selfetch	[1–3,5,6,9,11,12,25]

Note: Only those studies had been allocated to the respective adhesive system for which also clinical data did exist.

References for included in vitro studies:

[1] Bradna P, Vrbova R, Dudek M, Roubickova A, Housova D. Comparison of bonding performance of self-etching and etch-and-rinse adhesives on human dentin using reliability analysis. J Adhes Dent 2008;10:423–9.

[2] Frankenberger R, Lohbauer U, Tay FR, Taschner M, Nikolaenko SA. The effect of different air-polishing powders on dentin bonding. J Adhes Dent 2007;9:381–9.

[3] Peutzfeldt A, Asmussen E. Influence of eugenol-containing temporary cement on bonding of self-etching adhesives to dentin. J Adhes Dent 2006;8:31–4.

[4] De Munck J, Vargas M, Iracki J, Van Landuyt K, Poitevin A, Lambrechts P, Van Meerbeek B. One-day bonding effectiveness of new self-etch adhesives to bur-cut enamel and dentin. Oper Dent 2005;30:39–49.

[5] Moll K, Schuster B, Haller B. Dentin bonding of light- and self-curing resin composites using simplified total- and self-etch adhesives. Quintessence Int 2007;38:e27–35.

[6] Sadek FT, Goracci C, Cardoso PE, Tay FR, Ferrari M. Microtensile bond strength of current dentin adhesives measured immediately and 24 hours after application. J Adhes Dent 2005;7:297–302.

[7] Ulker M, Özcan M, Sengun A, Ozer F, Belli S. Effect of artificial aging regimens on the performance of self-etching adhesives. J Biomed Mater Res B Appl Biomater 2010;93:175–84.

[8] Salz U, Zimmermann J, Zeuner F, Moszner N. Hydrolytic stability of self-etching adhesive systems. J Adhes Dent 2005;7:107–16.

[9] Heintze SD, Thunpithayakul C, Armstrong SR, Rousson V. Correlation between microtensile bond strength data and clinical outcome of Class V restorations. Dent Mater 2010;27:114–25.

[10] Perdigão J, Gomes G, Gondo R, Fundingsland JW. In vitro bonding performance of all-in-one adhesives. Part I. Microtensile bond strengths. J Adhes Dent 2006;8:367–73.

[11] Van Landuyt KL, Mine A, De Munck J, Jaecques S, Peumans M, Lambrechts P, Van Meerbeek B. Are one-step adhesives easier to use and better performing? Multifactorial assessment of contemporary one-step self-etching adhesives. J Adhes Dent 2009;11:175–90.

[12] Furuse AY, Peutzfeldt A, Asmussen E. Effect of evaporation of solvents from one-step, self-etching adhesives. J Adhes Dent 2008;10:35–9.

[13] Chang JC, Pinzon M, Vuu TM, Powers JM. Tensile strengths of composite and dentin with 10 bonding agents. J Dent Res 2005;84

[14] Inoue S, Vargas MA, Abe Y, Yoshida Y, Lambrechts P, Vanherle G, Sano H, Van Meerbeek B. Microtensile bond strength of eleven contemporary adhesives to dentin. J Adhes Dent 2001;3:237–45.

[15] Shirai K, De Munck J, Yoshida Y, Inoue S, Lambrechts P, Suzuki K, Shintani H, Van Meerbeek B. Effect of cavity configuration and aging on the bonding effectiveness of six adhesives to dentin. Dent Mater 2005;21:110–24.

[16] Ateyah NZ, Elhejazi AA. Shear bond strengths and microleakage of four types of dentin adhesive materials. J Contemp Dent Pract. 2004;5:63–73.

[17] Wilder AD, Jr., Swift EJ, Jr., May KN, Jr., Waddell SL. Bond strengths of conventional and simplified bonding systems. Am J Dent 1998;11:114–7.

[18] Koh SH, Powers JM, Bebermeyer RD, Li D. Tensile bond strengths of fourth- and fifth-generation dentin adhesives with packable resin composites. J Esthet Restor Dent 2001;13:379–86.

[19] Holtan JR, Nystrom GP, Olin PS, Phelps RA, 2nd, Phillips JJ, Douglas WH. Bond strength of six dentinal adhesives. J Dent 1994;22:92–6.

– Table 1 (*Continued*).

[20] Courson F, Bouter D, Ruse ND, Degrange M. Bond strengths of nine current dentine adhesive systems to primary and permanent teeth. J Oral Rehabil 2005;32:296–303.
[21] Moll K, Park HJ, Haller B. Bond strength of adhesive/composite combinations to dentin involving total- and self-etch adhesives. J Adhes Dent 2002;4:171–80.
[22] Abdalla AI. Microtensile and tensile bond strength of single-bottle adhesives: a new test method. J Oral Rehabil 2004;31:379–84.
[23] Adebayo OA, Burrow MF, Tyas MJ. Bonding of one-step and two-step self-etching primer adhesives to dentin with different tubule orientations. Acta Odontol Scand 2008;66:159–68.
[24] Cardoso MV, Moretto SG, Carvalho RC, Russo EM. Influence of intrapulpal pressure simulation on the bond strength of adhesive systems to dentin. Braz Oral Res 2008;22:170–5.
[25] Yesilyurt C, Bulucu B. Bond strength of total-etch and self-etch dentin adhesive systems on peripheral and central dentinal tissue: a microtensile bond strength test. J Contemp Dent Pract 2006;7:26–36.
[26] Knobloch LA, Gailey D, Azer S, Johnston WM, Clelland N, Kerby RE. Bond strengths of one- and two-step self-etch adhesive systems. J Prosthet Dent 2007;97:216–22.
[27] Kenshima S, Reis A, Uceda-Gomez N, Tancredo Lde L, Filho LE, Nogueira FN, Loguercio AD. Effect of smear layer thickness and pH of self-etching adhesive systems on the bond strength and gap formation to dentin. J Adhes Dent 2005;7:117–26.
[28] Salz U, Bock T. Adhesion performance of new hydrolytically stable one-component self-etching enamel/dentin adhesives. J Adhes Dent 2010;12:7–10.
[29] Pecora N, Yaman P, Dennison J, Herrero A. Comparison of shear bond strength relative to two testing devices. J Prosthet Dent 2002;88:511–5.
[30] Toledano M, Osorio R, Ceballos L, Fuentes MV, Fernandes CA, Tay FR, Carvalho RM. Microtensile bond strength of several adhesive systems to different dentin depths. Am J Dent 2003;16:292–8.
[31] Jacobsen T, Finger WJ, Kanehira M. Air-drying time of self-etching adhesives vs bonding efficacy. J Adhes Dent 2006;8:387–92.
[32] Retief DH, Mandras RS, Russell CM. Shear bond strength required to prevent microleakage of the dentin/restoration interface. Am J Dent 1994;7:44–6.

specimen (between 5 and 90 depending on the studies, but on a limited number of teeth).

Data on the clinical performance of 28 adhesives was measured in subjects from 124 experiments conducted in 72 studies (between 20 and 134 subjects per experiment and between 1 and 4 experiments per study, 1 study involving up to 3 different adhesives). The patients were followed up between 1 and 8 years.

Data on the average in vitro performance of the different adhesives, which were measured in the different experiments, are shown in Fig. 1. The microtensile test consistently yielded higher bond strength values than the other two tests.

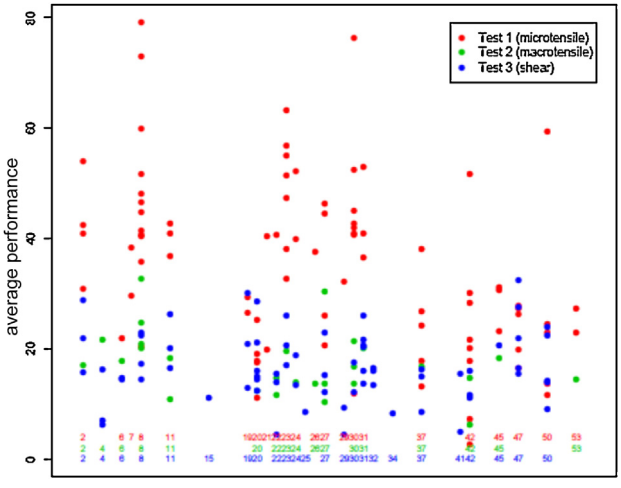

Fig. 1 – In vitro performance (MPa) of 28 adhesives measured with three test methods – pooled for all three tests. Each dot refers to an average performance calculated over a certain number of specimens from the same experiment. The numbers refer to the number of the AS (see Table 1).

With regard to the median bond strength, the 3-step etch and rinse and the 2-step self-etch adhesive systems tend to have higher bond strength values for all three test methods although the difference is less pronounced for the macroshear test (Table 2).

3.1. *Correlation between laboratory tests*

The highest correlation was found between Test 1 and Test 2 (rho = 0.66, $p = 0.007$), followed by the correlation between Test 1 and Test 3 (rho = 0.51, $p = 0.03$). The correlation between Test 2 and Test 3 was not significant (rho = 0.34, $p = 0.22$) (Fig. 2). However, these correlations were calculated from a maximum of 19 adhesive systems. The effect of the adhesive system was significant for Test 1 and Test 3 ($p < 0.001$) but not for Test 2 ($p = 0.11$). The effects of the adhesive systems are plotted in Fig. 2, showing the Spearman correlations between the in vitro performances measured by means of the three test methods.

3.2. *Correlation between laboratory tests and clinical performance*

Spearman correlations calculated between the four measures of clinical performance (R, MD, MI, CI) and the three in vitro tests are provided in Fig. 3. Fig. 4 shows only those 19 adhesives with at least 6 measurements of clinical performance from 2 experiments, and for which the in vitro performance was available for the 3 test methods. Although most correlations between clinical performance and in vitro performance measured by means of Test 3 were positive, none was significant. When considering all adhesives, Test 1 demonstrated a positive and significant correlation between microtensile bond strength and both marginal discoloration MD (rho = 0.54, $p = 0.01$) and the clinical index CI (rho = 0.56, $p = 0.01$). When

Table 2 – Median bond strength in relation to the test method and the adhesive class (in brackets number of studies).

	Self-etch 1 step	Self-etch 2 steps	Etch and rinse 2 steps	Etch and rinse 3 steps
Microtensile	23.7 ($n=34$)	41.3 ($n=19$)	40.7 ($n=23$)	49.4 ($n=10$)
Macrotensile	14.6 ($n=5$)	20.5 ($n=6$)	13.8 ($n=13$)	20.0 ($n=3$)
Macroshear	15.5 ($n=29$)	17.2 ($n=9$)	15.4 ($n=13$)	15.9 ($n=19$)

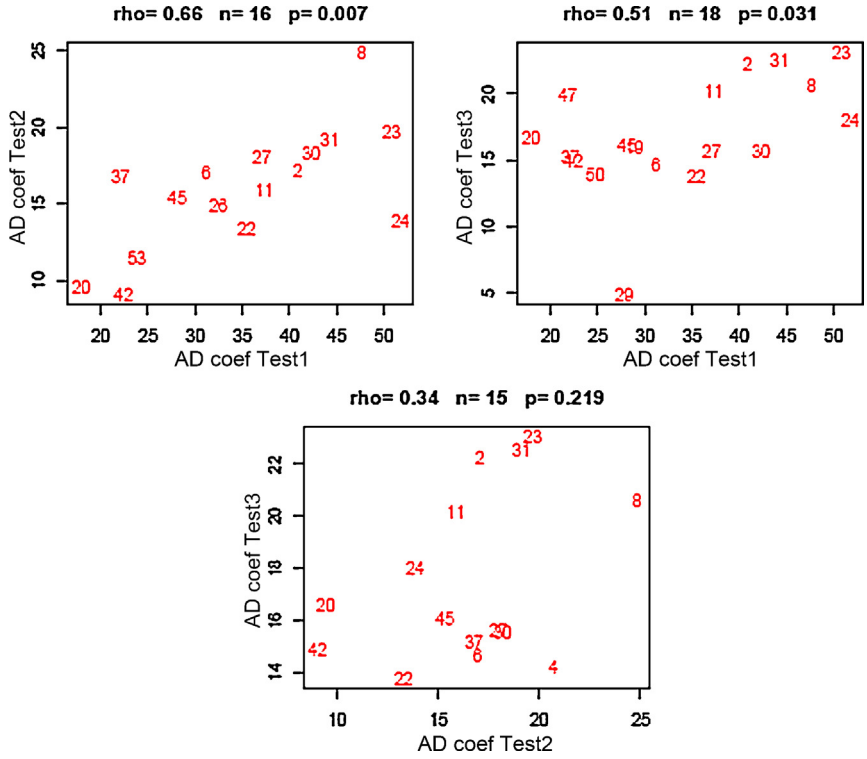

Fig. 2 – Spearman correlations between the three measures of in vitro performance (Test 1, Test 2, Test 3) obtained by means of coefficients estimated in a linear mixed model; the unit on the vertial and horizontal axis is MPa. The numbers refer to the number of the AS (see Table 1).

restricting the number of adhesives as explained above, the correlations were smaller and the significance was lost. On the other hand, Test 2 was also significantly correlated with marginal discoloration in each of these figures (e.g. rho = 0.62 and $p = 0.03$ in Fig. 4). There was no significant correlation between the test methods and retention R and marginal integrity (MI).

The correlation between the clinical and the in vitro performance might be further increased by considering a linear combination of the measurements provided by the three test methods. It is, however, difficult to perform such an analysis using only the 14 adhesives available for each method. Fig. 5 compares the correlations obtained when pooling the in vitro data from different studies and when considering the data from a single study. For Test 1, we selected study 22 and the 7 adhesives for which enough clinical data were available (No 8, 11, 21, 27, 29, 30, 37). For Test 2, we selected study 13 and the 7 adhesives for which enough clinical data were available (No 8, 11, 23, 24, 27, 37, 42). For Test 3, we selected study 8 and the 7 adhesives for which enough clinical data were available (No 6, 8, 22, 27, 29, 30, 31). Fig. 5 shows that the correlations are often higher when the results are pooled from different studies than when considering data from a single study.

3.3. *Variability of test results*

The percentage of variance explained by the factor *adhesive system* was similar for the three tests (Table 3). However, for Test 2 the effect of the adhesive system was not significant,

Table 3 – Variability of the three test methods.

	Microtensile test	Macrotensile test	Macroshear test
AS	95.838	16.264	18.316
Study	48.462	10.149	26.726
Residual	120.137	32.630	10.334
% explained by adhesive	36.2	27.5	33.1

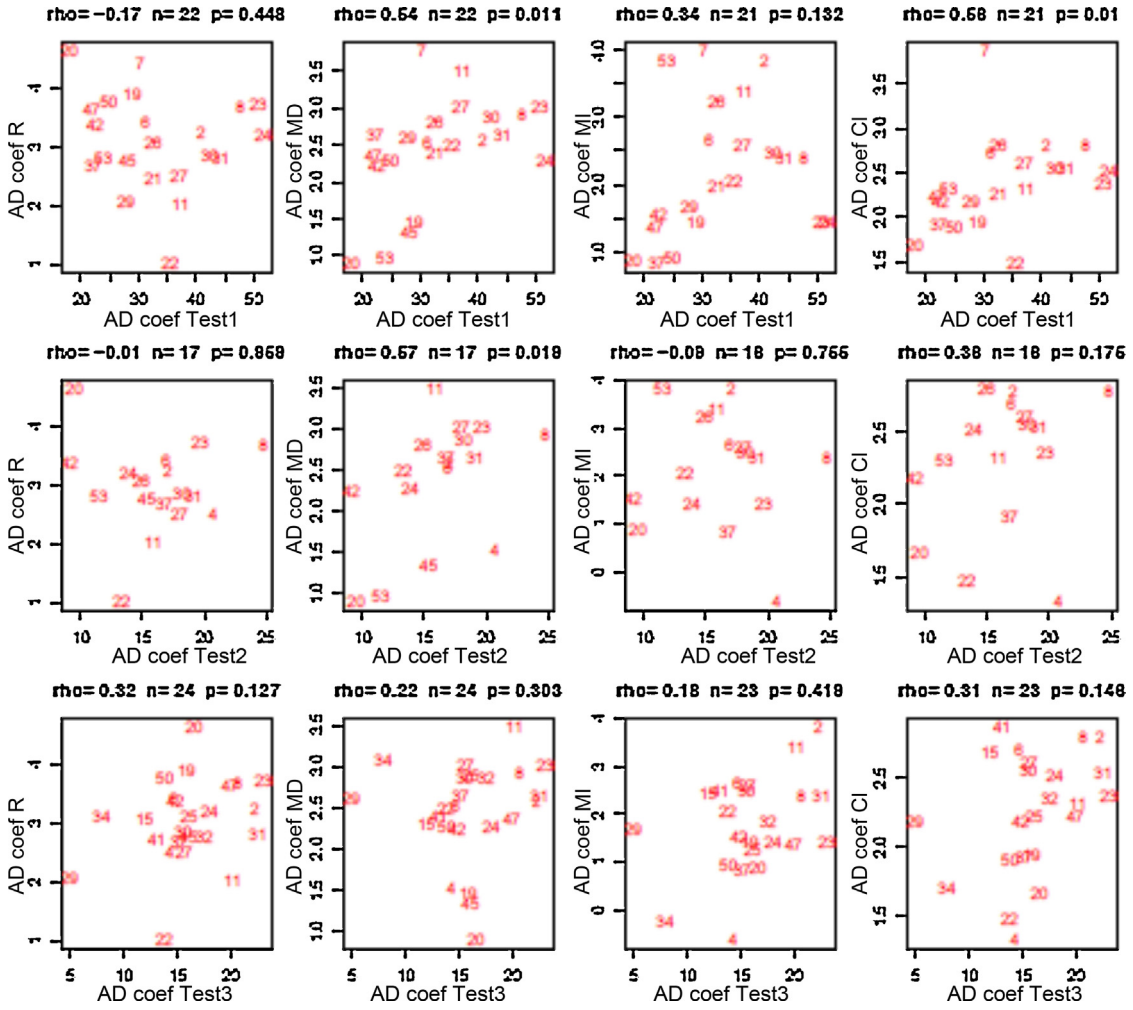

Fig. 3 – Spearman correlations between the four measures of clinical performance (R, MD, MI, CI on the vertical axis) and the three measures of in vitro performance (Test 1, Test 2, Test 3 on the horizontal axis, unit MPa) obtained by means of coefficients estimated in a linear mixed model using data from all adhesive systems. The numbers refer to the number of the AS (see Table 1).

i.e. we cannot exclude that the true percentage of variance is equal to zero for this test (note, however, the smaller sample size for this test). When calculating the variance among the estimated effect of the adhesive systems using only the 11 adhesives with at least 6 measurements of clinical performance from 2 experiments and for which the in vitro performance was available for the 3 test methods, these percentages of variance were estimated at 53% for R, 15% for MD, 53% for MI and 31% for CI (using 50 patients), and at 38% for Test 1, 28% for Test 2 and 24% for Test 3.

As far as the variability of the clinical studies is concerned, the percentage of variance explained by the factor adhesive system was somewhat higher (and hence the variability a bit lower) in the clinical studies (including 50 patients) compared

Table 4 – Variability of clinical studies.

	R	MD	MI	CI
Adhesive	0.556	0.469	1.284	0.268
Study	0.207	0.394	1.140	0.158
Experiment	0.114	0.096	0.192	0.041
Residual with a single patient	12.990	13.110	14.987	6.349
Residual with 50 patients	0.260	0.262	0.300	0.127
% explained by adhesive with 50 patients	48.9	38.4	44.0	45.1

Note that the residual variance with 50 patients is obtained as the residual variance with a single patient divided by 50 (one could calculate in a similar manner the residual variance with another number of patients).

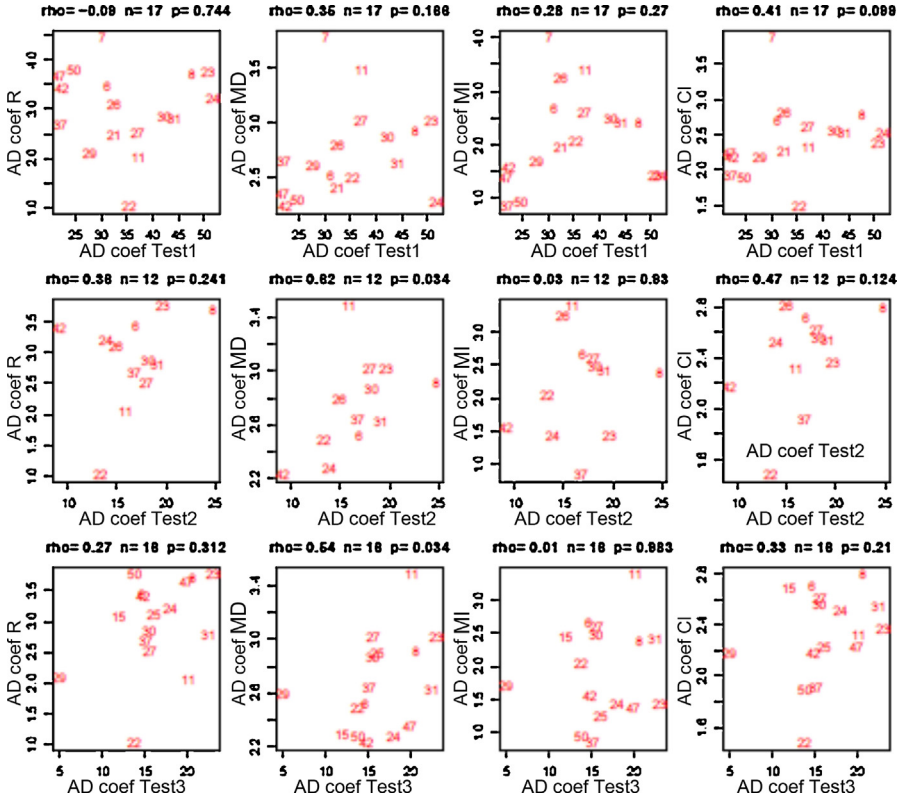

Fig. 4 – Spearman correlations between the four measures of clinical performance (R, MD, MI, CI on the vertical axis) and the three measures of in vitro performance (Test 1, Test 2, Test 3 on the horizontal axis, unit MPa) obtained by means of coefficients estimated in a linear mixed model restricting to the (available) 19 adhesives with at least 6 measurements of clinical performance from 2 experiments. The numbers refer to the number of the AS (see Table 1).

to that of the laboratory results (Table 4). About 49% of the variability of retained restorations could be explained by the adhesive system.

4. Discussion

The present meta-analysis confirmed the high variability of bond strength test results observed in other systematic reviews and meta-analyses on that topic [10,13,18]. The inclusion of those studies which tested at least four adhesive systems in the same study did not reduce the variability. The present study revealed that only about 30% of the variability can be explained by the most important test parameter, namely the adhesive system. But also the variability of the clinical studies was high, although somehow lower than that of the laboratory tests: about 50% of the variability of retained cervical restorations could be explained by the adhesive system. However, it is important to state that both the variability of clinical and laboratory tests decreases the correlation between both and makes the prediction regarding the performance of a specific adhesive system difficult.

Up to date, no systematic studies have examined the reasons for the high variability of bond strength test results if the adhesive system is applied with the same test parameters but at different test institutes. The most likely influencing factors, also mentioned in other studies, are parameters which are difficult to standardize, such as the operator who produces the specimens and carries out the test as well as the tooth substance to which the composite is bonded. Other potential influencing factors are the method to restrict the bonded area for the shear and tensile test (if done at all), the method and device to cut the specimens (important for the microtensile test), the type of composite, the statistical handling of pre-test failures, etc.

The effect of operator variability has been addressed by several studies [19–25]. All of these studies exclusively confirmed the huge variability between different operators. Some of them concluded that inexperienced operators who were not familiar with bonding techniques generally produced lower bond strength values than experienced operators. In one study, experienced faculty members produced higher bond strength values with the same products and the same instructions than operators without any bond strength test experience [21]. The differences between two operators were up to 100% (e.g. 12 MPa vs 24 MPa) for the same product. The coefficient of variation for the same operator was more than 50%. In another study, general practitioners performed shear bond strength tests with four adhesives systems. The results revealed the same variability but also demonstrated lower bond strength values than reported in the literature for the same product [26]. In this same study, the bond strength results improved significantly after a 90 min lecture about bonding principles and materials. The effect of operator

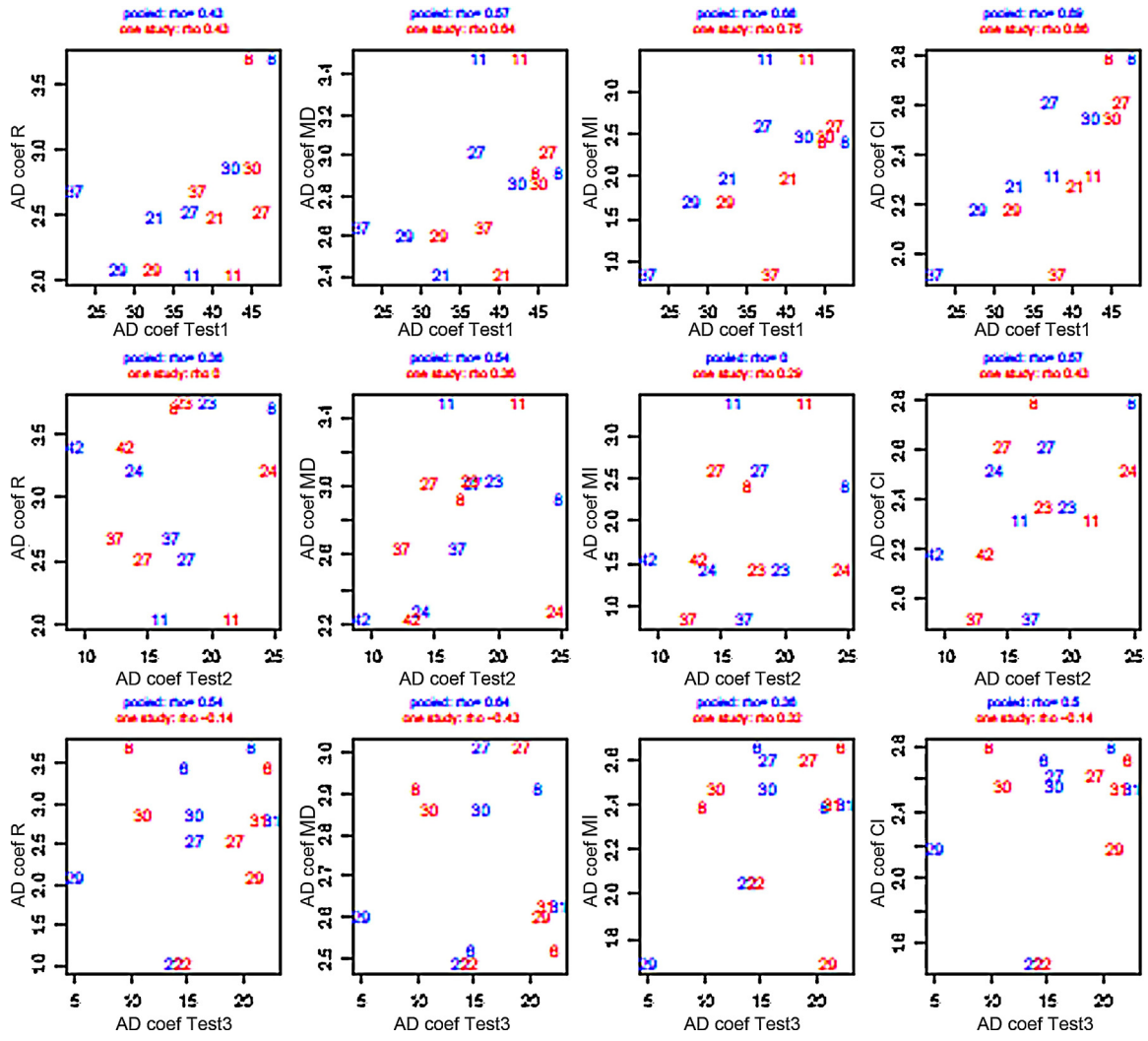

Fig. 5 – Spearman correlations between the four measures of clinical performance (R, MD, MI, CI on the vertical axis) and the three measures of in vitro performance (Test 1, Test 2, Test 3 on the horizontal axis, unit MPa) of seven adhesives obtained when pooling the results of all studies (blue numbers) and when keeping only one study (red numbers). The numbers refer to the number of the AS (see Table 1).

variability could be ruled out to a great extent if robotic devices were to be constructed, automatically producing and bonding the specimens to the tooth substance. However, no effort has been made in this direction. The effect of different batches of adhesive systems tested at the various test institutes can be regarded as negligible. It seems though that 1-step self-etch systems are associated with lower microtensile strength values than the other three types of adhesive groups (self-etch – 2 steps, etch and rinse 2 and 3 steps). No such clear differentiation can be observed with the tensile bond strength and shear bond strength tests.

In the first extensive meta-analysis concerning influencing factors on bond strength [18], the following factors were defined and are listed in descending order according to the statistically proven importance: dentin depth, crosshead speed, specimen storage time and tooth storage maximum time, bonding area, tooth storage temperature, specimen storage temperature and composite stiffness. The influence of the operator was, however, not specifically investigated in this analysis. In the most recent meta-analysis on that topic [13], the main result showed that, next to the adhesive system, the testing institute influences the result the most. Other findings were as follows (1) the microtensile test discriminates more effectively between different adhesive systems than the macroshear test; (2) thermocycling has a negligible influence on the decrease of bond strength – both, for the microtensile and macroshear test; (3) long-term storage in water significantly decreases the bond strength if tested with the microtensile method but not with the macroshear test. It could be the case that if individual test centers are to establish individual rankings between different adhesive systems the correlation of the rankings with clinical retention would be better.

With regard to the correlation between bond strength test results and the retention rate of prospective clinical studies of cervical restorations, no correlation was found. This is in contrast to a preliminary study which showed a good correlation with retention [27]. This correlation was, however, only based on six adhesive systems and the selection of the studies

was less restrictive. In the present study, the only consistent correlation was found between the micro- and macrotensile tests and marginal staining when all adhesive systems were included in the analysis. When restricting the analysis only to those adhesive systems for which at least six recall measurements from two different studies were available, again the macrotensile and microtensile bond tests had a significant correlation with marginal staining. The correlation between the microtensile test and marginal staining has also been established in an earlier study based on data from one test institute [14]. The correlation was somehow better when the test was performed after water storage for 6 months. Marginal discoloration is indicative for gap formation and macroleakage [28,29] and could be regarded as precursor for a subsequent retention loss of the restoration. However, this has never been systematically proven. Data of a meta-analysis on the clinical performance of cervical restorations indicated that the precursor theory might at least only be partially true as the frequency of restorations with stained margins was 2–3 times higher than the frequency of lost restorations [16].

Another important factor has not been taken into consideration up to date. In many clinical cervical restorations the materials are placed in eroded dentin which is only cleaned with pumice. This was the case in at least 50% of the clinical studies analysed by Heintze and colleagues [16]. They furthermore noticed that retention of fillings placed in unprepared cervical defects was significantly lower than those placed in prepared cervical defects. This finding is supported by an in vitro study by Zimmerli et al. [30], showing that adhesive systems perform significantly worse in eroded dentin than in non-eroded dentin.

Furthermore, the long term water storage of specimens can improve the correlation with retention loss as shown by Van Meerbeek et al. [15]. The correlation for specimens stored for a prolonged time in water was higher for 5-year data than for 2-year data. For the present study, only results from studies with 24 h of water storage were included as up to date, only few studies could be found with prolonged water storage of specimens (>3 months) that matched our inclusion criteria. Prolonged water storage decreases the bond strength when compared to 24 h storage as the recently performed meta-analysis by De Munck and colleagues demonstrated [13]. In this meta-analysis, studies which were published between 2004 and 2009 and which tested at least two commercially adhesive systems were included. However, the decrease was only statistically significant for the 1-step self-etching adhesive systems but not for the other three adhesive categories. Furthermore, thermocycling had no significant impact on bond strength irrespective of the adhesive class or the test method. However, only 17% of the studies included in this meta-analysis performed prolonged water storage. The authors of the present study would have also liked to include studies with prolonged water storage. But it remains questionable whether the correlation with clinical parameters will improve if more data with prolonged water storage become available.

Ideally, bond strength tests shall predict the clinical performance of dental materials and allow developers of new products to choose between various formulations. One likely explanation for the lack of correlation of the absolute value of bond strength with retention is that above a certain threshold value, which is most likely different for each research institute, the absolute number of bond strength is irrelevant for the clinical performance or at least for the retention rate of cervical restorations.

Of course, also the results of clinical trials involving the same materials are variable [16,31]. This can be due to three reasons: (1) patient-related factors do play a significant role which are unknown and cannot be tested in the laboratory, (2) patient- and defect-related differences of the dentinal substrate due to erosion, caries or mechanical defects, and (3) application of the materials and the evaluation of the restorations do not follow standardized protocols. One possible patient-related factor for retention loss are occlusal parafunctions which may not be causal but play an additional role for the development of cervical wedge-shaped defects and the retention loss [32]; the etiology of wedge-shaped defects, however, must be regarded as multifactorial [33]. By adopting standardized test protocols and examination parameters (e.g. refined evaluation criteria like SQUACE), it might be possible to reduce the variability of clinical outcome parameters [34,35].

A pragmatic way to use bond strength tests in the laboratory to choose between different variants of an adhesive system and/or to prove its clinical efficacy could be as follows:

1 To prove that the institute-related critical threshold bond strength value is surpassed.
2 To prove that the inter-operator variability is low (e.g. less than 20%).
3 To prove that the inter-institute variability is low (e.g. less than 30%).
4 To prove that storage of the product over time (e.g. 12 months at room temperature) does not lower the bond strength below the institute-related critical threshold bond strength value.

Furthermore, other laboratory tests, such as the marginal adaptation of fillings to human enamel, which have a clinical correlation with marginal staining, should be performed to gain more information on the possible clinical performance of an adhesive system [5,36].

All three hypotheses had to be rejected:

1. There was a significant correlation between microtensile test and macrotensile test as well as between microtensile test and macroshear test.
2. There was a moderate correlation between microtensile and macrotensile test and marginal staining but not between these tests and retention and marginal integrity.
3. Pooling of data slightly improves the correlation with clinical parameters.

Summary

Both, the clinical and the in vitro measurements showed a high variability. In the present analysis, we have modeled the averages of repeated clinical and in vitro measurements obtained from different studies and experiments, and we could find some significant positive - albeit moderate - correlations between measurements of clinical and in vitro

performance notably between tensile bond strength and marginal discoloration. While the absolute bond strength is best used with caution to predict clinical outcome, the observed inter-institute and – operator variability could be a useful tool to test the technique sensitivity and tolerance of an adhesive-composite system. One should, however, not rely solely on bond strength tests to predict the clinical performance of an adhesive system but one should conduct additional laboratory tests such as tests on the marginal adaptation of fillings in extracted teeth and the retention loss of restorations in non-retentive cavities after artificial aging such as prolonged thermocycling.

REFERENCES

[1] Bowen RL. Adhesive bonding of various materials to hard tooth tissues. I. Methods of determining bond strength. J Dent Res 1965;44:690–5.
[2] Retief DH. Standardizing laboratory adhesion tests. Am J Dent 1991;4:231–6.
[3] Söderholm KJ. Correlation of in vivo and in vitro performance of adhesive restorative materials: a report of the ASC MD156 task group on test methods for the adhesion of restorative materials. Dent Mater 1991;7:74–83.
[4] Pashley DH, Sano H, Ciucchi B, Yoshiyama M, Carvalho RM. Adhesion testing of dentin bonding agents: a review. Dent Mater 1995:11.
[5] Sudsangiam S, van Noort R. Do dentin bond strength tests serve a useful purpose? J Adhes Dent 1999;1:57–67.
[6] Stamatacos-Mercer C, Hottel TL. The validity of reported tensile bond strength utilizing non-standardized specimen surface areas. An analysis of in vitro studies. Am J Dent 2005;18:105–8.
[7] Burke FJ, Hussain A, Nolan L, Fleming GJ. Methods used in dentine bonding tests: an analysis of 102 investigations on bond strength. Eur J Prosthodont Restor Dent 2008;16:158–65.
[8] Braga RR, Meira JB, Boaro LC, Xavier TA. Adhesion to tooth structure: a critical review of macro test methods. Dent Mater 2010;26:e38–49.
[9] Armstrong S, Geraldeli S, Maia R, Raposo LH, Soares CJ, Yamagawa J. Adhesion to tooth structure: a critical review of "micro" bond strength test methods. Dent Mater 2010;26:e50–62.
[10] Scherrer SS, Cesar PF, Swain MV. Direct comparison of the bond strength results of the different test methods: a critical literature review. Dent Mater 2010;26:e78–93.
[11] Salz U, Bock T. Testing adhesion of direct restoratives to dental hard tissue – a review. J Adhes Dent 2010;12:343–71, http://dx.doi.org/10.3290/j.jad.a19741.
[12] Finnema KJ, Ozcan M, Post WJ, Ren Y, Dijkstra PU. In-vitro orthodontic bond strength testing: a systematic review and meta-analysis. Am J Orthod Dentofac Orthop 2010;137:615–22.e3.
[13] De Munck J, Mine A, Poitevin A, Van Ende A, Cardoso MV, Van Landuyt KL, et al. Meta-analytical review of parameters involved in dentin bonding. J Dent Res 2012;91:351–7.
[14] Heintze SD, Thunpithayakul C, Armstrong SR, Rousson V. Correlation between microtensile bond strength data and clinical outcome of Class V restorations. Dent Mater 2010;27:114–25.
[15] Van Meerbeek B, Peumans M, Poitevin A, Mine A, Van Ende A, Neves A, et al. Relationship between bond-strength tests and clinical outcomes. Dent Mater 2010;26:e100–21.
[16] Heintze SD, Ruffieux C, Rousson V. Clinical performance of cervical restorations – a meta-analysis. Dent Mater 2010;26:993–1000.
[17] Abdalla AI. Microtensile and tensile bond strength of single-bottle adhesives: a new test method. J Oral Rehabil 2004;31:379–84.
[18] Leloup G, D'Hoore W, Bouter D, Degrange M, Vreven J. Meta-analytical review of factors involved in dentin adherence. J Dent Res 2001;80:1605–14.
[19] Sano H, Kanemura N, Burrow MF, Inai N, Yamada T, Tagami J. Effect of operator variability on dentin adhesion: students vs dentists. Dent Mater J 1998;17:51–8.
[20] Miyazaki M, Onose H, Moore BK. Effect of operator variability on dentin bond strength of two-step bonding systems. Am J Dent 2000;13:101–4.
[21] Söderholm KJ, Guelmann M, Bimstein E. Shear bond strength of one 4th and two 7th generation bonding agents when used by operators with different bonding experience. J Adhes Dent 2005;7:57–64.
[22] Adebayo OA, Burrow MF, Tyas MJ. Bond strength test: role of operator skill. Aust Dent J 2008;53:145–50.
[23] Unlu N, Gunal S, Ulker M, Ozer F, Blatz MB. Influence of operator experience on in vitro bond strength of dentin adhesives. J Adhes Dent 2012;14:223–7.
[24] Moll K, Fritzenschaft A, Haller B. In vitro comparison of dentin bonding systems: effect of testing method and operator. Quintessence Int 2004;35:845–52.
[25] Söderholm KJ, Soares F, Argumosa M, Loveland C, Bimstein E, Guelmann M. Shear bond strength of one etch-and-rinse and five self-etching dental adhesives when used by six operators. Acta Odontol Scand 2008;66:243–9.
[26] Bouillaguet S, Degrange M, Cattani M, Godin C, Meyer JM. Bonding to dentin achieved by general practitioners. Schweiz Monatsschrift Zahnmed 2002;112:1006–11.
[27] Heintze SD, Rousson V. Pooling of dentin microtensile bond strength data improves clinical correlation. J Adhes Dent 2011;13:107–10.
[28] Hayashi M, Tsuchitani Y, Kawamura Y, Miura M, Takeshige F, Ebisu S. Eight-year clinical evaluation of fired ceramic inlays. Oper Dent 2000;25:473–81.
[29] Kidd EA, Beighton D. Prediction of secondary caries around tooth-colored restorations: a clinical and microbiological study. J Dent Res 1996;75:1942–6.
[30] Zimmerli B, De Munck J, Lussi A, Lambrechts P, Van Meerbeek B. Long-term bonding to eroded dentin requires superficial bur preparation. Clin Oral Investig 2012;16:1451–61.
[31] Heintze SD, Rousson V. Clinical effectiveness of direct class II restorations – a meta-analysis. J Adhes Dent 2012;14:407–31.
[32] Litonjua LA, Andreana S, Patra AK, Cohen RE. An assessment of stress analyses in the theory of abfraction. Biomed Mater Eng 2004;14:311–21.
[33] Bernhardt O, Gesch D, Schwahn C, Mack F, Meyer G, John U, et al. Epidemiological evaluation of the multifactorial aetiology of abfractions. J Oral Rehabil 2006;33:17–25.
[34] Hickel R, Roulet JF, Bayne S, Heintze SD, Mjör IA, Peters M, et al. Recommendations for conducting controlled clinical studies of dental restorative materials (Science Committee Project 2/98 – FDI World Dental Federation). J Adhes Dent 2007;9(Suppl. 1):121–47.
[35] Peschke A. The semi-quantitative evaluation of restorations (SQUACE) – a tool to increase sensitivity. J Dent Res 2009;88(Special issue A) [Symposium no. 154].
[36] Heintze SD. Clinical relevance of tests on bond strength, microleakage and marginal adaptation. Dent Mater 2013;29:59–84.