The effect of surface treatment and thermocycling on the shear bond strength of orthodontic brackets to the Y-TZP zirconia ceramics: A systematic review

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ABSTRACT

Introduction: Various surface pre-treatment methods have been adapted to optimize the bonding between the zirconia ceramics and the orthodontic brackets.

Objective: This review is aimed at systematically analyzing the relevant data available in the literature, to find out the most effective and durable bonding protocol.

Methods: Database search was conducted in PubMed, Scopus, and ScienceDirect, during September 2020. The review was conducted according to the PRISMA guidelines.

Results: Based on the inclusion criteria, 19 articles were selected for qualitative analysis. Meta-analysis could not be performed due to the heterogeneity of the methodology among the studies. Most of the studies scored medium risk of bias. Compared to the untreated surface, surface pretreatments like sandblasting and lasers were advantageous. Primers and universal adhesive were mostly used as an adjunct to the mechanical pretreatment of the zirconia surface. In most studies, thermocycling seemed to lower the shear bond strength (SBS) of the orthodontic brackets.

Conclusion: Based on this qualitative review, surface pretreatments with lasers and sandblasting can be suggested to optimize the bracket bond strength. To clarify this finding, meta-analysis is anticipated. Hence, high heterogeneity of the included studies demands standardization of the methodology.

Keywords: Y-TZP zirconia. Orthodontic brackets. Shear bond strength. Surface treatment.
RESUMO

Introdução: Diferentes métodos de pré-tratamento da superfície foram adaptados para otimizar a colagem entre os braquetes ortodônticos e as cerâmicas de zircônia.

Objetivo: A presente revisão teve como objetivo analisar, de forma sistemática, os dados relevantes na literatura, para buscar o protocolo de colagem mais efetivo e duradouro.

Métodos: As buscas foram feitas em setembro de 2020, nas seguintes bases de dados: PubMed, Scopus e ScienceDirect. A revisão foi feita de acordo com as diretrizes do PRISMA.

Resultados: Com base nos critérios de inclusão, 19 artigos foram selecionados para análise qualitativa. A metanálise não pode ser feita, devido à heterogeneidade na metodologia dos estudos incluídos. A maior parte dos estudos apresentou risco de viés moderado. Comparadas às superfícies não tratadas, as superfícies com pré-tratamento usando jateamento ou laser apresentaram vantagem. Primers e adesivos universais foram mais usados como adjuntos ao pré-tratamento mecânico da superfície de zircônia. Na maioria dos estudos, a termociclagem parece ter reduzido a resistência ao cisalhamento dos braquetes ortodônticos.

Conclusões: Com base nessa revisão qualitativa, os pré-tratamentos de superfície com laser e jateamento podem ser sugeridos para otimizar a resistência ao cisalhamento dos braquetes. Para esclarecer esse achado, uma metanálise é necessária. Para isso, faz-se necessária a padronização da metodologia, para lidar com a alta heterogeneidade dos estudos incluídos.

Palavras-chave: Zircônia Y-TZP. Braquetes ortodônticos. Resistência ao cisalhamento. Tratamento de superfície.
INTRODUCTION

With the increasing demand for esthetics and the introduction of the CAD/CAM devices, zirconia ceramics have gained much popularity in modern Dentistry. Zirconia claimed superiority in terms of mechanical properties, biocompatibility, precision and esthetics.\textsuperscript{1,2} The yttrium-stabilized tetragonal zirconia polycrystal (Y-TZP) is the form most commonly used in Dentistry. The material is known for the phase transformation from tetragonal to monoclinic due to stressful conditions, achieving fracture resistance.\textsuperscript{3} It has been used extensively to make inlays, onlays, crowns, post and core systems, and frameworks for porcelain fused to zirconia restorations.\textsuperscript{4} Hence, with the increasing use of zirconia restorative materials, it is becoming more common for orthodontists to bond orthodontic brackets to a Y-TZP surface. However, due to the chemical inertness and resistance to acid-etching, bonding composite resin to the zirconia surface can be challenging. Thus, various surface treatment methods — such as mechanical, chemical, or combined — have been introduced to improve the bond strength of zirconia ceramics.

The \textit{in-vitro} shear bond strength (SBS) is the most commonly used test, due to its simplicity and resemblance to the shear force exerted during mastication. In addition, aiming at testing
the durability of these methods, the material can be exposed to water at a certain temperature, simulating an oral environment for a determined period — a procedure known as thermocycling.

Previously, reviews were mostly based on the bond strength between the luting cement and the zirconium surface; overlooking the impact of orthodontic brackets. Therefore, this study is aimed to perform a systematic review of the in-vitro studies that reported the effect of different surface conditioning and aging on the shear bond strength of orthodontic brackets to the Y-TZP zirconia ceramics.

MATERIAL AND METHODS

SEARCH STRATEGY
The review was conducted by following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The research question of this review was: Which surface treatment is best suited to optimize the shear bond strength of orthodontic brackets to Y-TZP zirconia ceramics? The question was developed concerning the following PICO (population, intervention, comparison, and outcome): Y-TZP zirconia, surface treatment, thermocycling, no thermocycling, comparison between surface treatment methods with the resultant shear bond strength (SBS), respectively.
The electronic databases PubMed, Scopus, and ScienceDirect were searched, using the following keywords: orthodontic brackets, shear bond strength, zirconium, ceramic surface, and thermocycling. Additionally, Google Scholar was searched with the same keywords. The references of the selected studies were also checked for any missing relevant studies. All searches were performed in September 2020. The search was confined to the original articles written in English language, published between the years 2001 to 2020. All the duplicates were resolved by the Endnote X7 software (Thompson Reuters, Philadelphia, PA, USA). The search strategy is summarized in Table 1.

Table 1: Database search strategy.

| Name of Database | Last date of Search | Keywords                                      | Studies found | Studies selected |
|------------------|---------------------|-----------------------------------------------|---------------|------------------|
| Pubmed Central   | 12/09/2020          | Orthodontic brackets, shear bond strength,    | 28            | 12               |
|                  |                     | zirconium, ceramic surface, thermocycling     |               |                  |
| Scopus           | 12/09/2020          |                                               | 08            | 08               |
| ScienceDirect    | 12/09/2020          |                                               | 15            | 2                |
| Google Scholar   | 15/09/2020          |                                               | 1680          | 86               |

STUDY SELECTION

Two independent reviewers screened the titles and abstracts of all the studies found. The articles were selected according to the following inclusion and exclusion criteria:

INCLUSION CRITERIA

1) Studies that bonded orthodontic brackets to Y-TZP surface.
2) Studies that conditioned the surface before bonding.
3) Studies with a well-designed shear bond strength test.
4) *In-vitro* experimental and observational studies.
5) Full-text original articles.

**EXCLUSION CRITERIA**

1) *In-vivo* studies and clinical trials.
2) Studies testing materials other than orthodontic brackets and Y-TZP zirconia, such as resins or composite cement, buccal tubes, enamel, dentine, zirconium fused to porcelain or lithium silicate infused with zirconium, etc.

The agreement between both reviewers was confirmed by Cohen’s kappa statistics. A third reviewer was consulted in the event of any disagreement.

**DATA EXTRACTION**

Two reviewers independently reviewed the full-text articles and extracted the following data in tabulated form: study year, sample size, surface treatment method, adhesives and brackets used, storage, method of thermocycling, and the resultant shear bond strength (Table 2). Agreement between the reviewers was assessed by Cohen’s Kappa statistics. The third reviewer’s opinion was considered to resolve any disagreement.
Table 2: Data extraction.

| Study              | Sample | Surface treatment                                                                 | Adhesive                        | Brackets                  | Storage                        | Thermocycling                               | Bond strength (MPa) |
|--------------------|--------|------------------------------------------------------------------------------------|---------------------------------|---------------------------|---------------------------------|----------------------------------------------|---------------------|
| Akay et al.12 (2020) | 48     | G1) Er:YAG laser (2W) G2) Nd:YAG laser (2W) G3) Sandblasting (SiO₂) G4) 9.6% hydrofluoric acid | Transbond XT light cured composite | Maxillary central incisor metal brackets | 37°C deionized water for 30 days | 2,000 cycles between 5±2 - 55±2°C with 30s dwelling time | G1: 5.5 ± 0.79 G2: 4.88 ± 0.82 G3: 7.42 ± 0.92 G4: 3.58 ± 0.75 |
| Ju et al.4 (2020)   | 80     | G1) Sandblasting + Clearfil ceramic primer on zirconia surface G2) Sandblasting + Clearfil ceramic primer on bracket base G3) Sandblasting + Clearfil ceramic primer on both zirconia surface and bracket base | Transbond XT primer + Transbond XT light cure composite | Monocrystalline ceramic brackets | At 37°C and humidity 100% for 24h. | 10,000 cycles between 5º - 55ºC with 30s dwelling time | Mean and standard deviation not included |
| Ju et al.2 (2019)   | 60     | G1) Sandblasting + Clearfil Ceramic primer + orthodontic primer G2) Sandblasting + universal adhesive G3) Sandblasting + Clearfil ceramic primer + universal adhesive | Transbond XT light cured composite | Maxillary central incisor ceramic brackets | 37°C and relative humidity 100% incubator for 24h. | 10,000 cycles between 5º - 55ºC with 30s dwelling time | Before thermocycling: G1: 9.78 ± 1.94 G2: 9.86 ± 1.33 G3: 9.16 ± 0.78 After thermocycling: G1: 8.16 ± 1.78 G2: 4.99 ± 0.99 G3: 4.31 ± 1.02 |
| Mehmeti et al.26 (2019) | 48     | G1) 37% phosphoric acid for 120s + silane primer G2) 5% hydrofluoric acid + silane primer | Transbond XT primer + Transbond XT light cure composite | i) Metal brackets ii) Polycrystalline ceramic brackets | Not mentioned | 5,800 cycles between 5º - 55ºC with 10s dwelling time | Metal brackets: G1: 10.85 ± 5.84 G2: 8.52 ± 4.72 Ceramic brackets: G1: 11.84 ± 7.30 G2: 8.99 ± 5.36 |
| Cetik et al.15 (2019) | 40     | G1) Sandblasting + Silane primer G2) Er:YAG laser + Silane primer | Brack Fix primer + Brack 1Fix light cured composite | i) Mandibular anterior metal brackets ii) Mandibular anterior ceramic brackets | Not done | Not done | Metal brackets: G1: 23.29 ± 5.34 G2: 21.59 ± 4.03 Ceramic brackets: G1: 20.06 ± 4.05 G2: 17.55 ± 3.88 |
### Table 2 - continuation: Data extraction.

| Study                  | Sample | Surface treatment                                      | Adhesive                                   | Brackets                          | Storage                                         | Thermocycling                        | Bond strength (MPa)       |
|------------------------|--------|--------------------------------------------------------|--------------------------------------------|-----------------------------------|------------------------------------------------|--------------------------------------|--------------------------|
| Douara et al.²⁷ (2019) | 45     | G1) Sandblasting (Al₂O₃) + universal bonding resin (Assure plus)  
               |                                             | Transbond XT primer + Transbond XT light cure composite resin | Monocrystalline ceramic brackets  | 37°C distilled water for 24 hrs.                   | 500 cycles between 5º - 55ºC with 30s dwelling time | G1: 2.50 ± 0.75  
               |                                             |                                           |                                             | G2: 7.81 ± 2.81  
               |                                             |                                           |                                             | G3: 8.15 ± 2.41  
| Garcia-Sanz et al.⁸ (2018) | 90     | G1) No treatment  
               |                                             | Transbond XT primer + Transbond XT light cure composite | Maxillary incisor metal brackets | 37°C distilled water for 24 hrs.                   | Not done                        | G1: 3.87 ± 0.77  
               |                                             | G2) Sandblasting  
               |                                             |                                             |                                             | G2: 4.25 ± 0.51  
               |                                             | G3) Femtosecond Ti:Sapphire laser output power- 300 mW, inter-groove distance 60 μm  
               |                                             |                                             |                                             | G3: 5.92 ± 1.12  
               |                                             | G4) Femtosecond Ti:Sapphire laser output power- 200 mW, inter-groove distance 100 μm  
               |                                             |                                             |                                             | G4: 3.74 ± 0.10  
               |                                             | G5) Femtosecond Ti:Sapphire laser output power- 40 mW, inter-groove distance 60 μm.  
               |                                             |                                             |                                             | G5: 3.91 ± 0.53  
               |                                             | G6) Femtosecond Ti:Sapphire laser output power- 200 mW, inter-groove distance 60 μm  
               |                                             |                                             |                                             | G6: 5.68 ± 0.94  
| Byeon et al.¹⁴ (2017)  | 130    | G1) Polishing  
               |                                             | Transbond XT light cured composite | Maxillary central incisor metal brackets | 37 ± 1°C distilled water for 24 hrs.                   | 5,000 cycles between 5º - 55ºC with 30s dwelling time | Before thermocycling: G1: 2.6 ± 1.1  
               |                                             | G2) Sandblasting  
               |                                             |                                             |                                             | G2: 4.98 ± 1.28  
               |                                             | G3) Sandblasting + Silane primer  
               |                                             |                                             |                                             | G3: 5.13 ± 0.85  
               |                                             | G4) Sandblasting + MDP primer  
               |                                             |                                             |                                             | G4: 11.92 ± 1.51  
               |                                             | G5) Sandblasting + MDP containing silane primer  
               |                                             |                                             |                                             | G5: 13.36 ± 2.31  
               |                                             | After thermocycling: G1: 0.70 ± 0.4  
               |                                             |                                             |                                             | G2: 0.8 ± 0.3  
               |                                             |                                             |                                             | G3: 1.5 ± 0.4  
               |                                             |                                             |                                             | G4: 5.4 ± 3.5  
               |                                             |                                             |                                             | G5: 5.7 ± 1.2  

Byeon et al.¹⁴ (2017)
### Table 2 - continuation: Data extraction.

| Study                  | Sample | Surface treatment                                      | Adhesive                  | Brackets            | Storage | Thermocycling | Bond strength (MPa) | Non-thermocycled Bond strength (MPa) |
|------------------------|--------|--------------------------------------------------------|---------------------------|---------------------|---------|---------------|---------------------|-------------------------------------|
| Garcia-Sanz et al.     | 300    | G1) No treatment                                       | Transbond XT primer + Transbond XT light cure composite | i) Maxillary central incisor metal brackets.  
G2) Sandblasting       |         | G3) Tribochemical silica coating + Silane primer       |                           | ii) Maxillary central incisor ceramic brackets.  
G4) Femtosecond laser (200 mW) |         | G5) Sandblasting + Femtosecond laser (200 mW)         |                           |          | Not mentioned | Metal brackets:  
G1: 4.23 ± 0.89  
G2: 4.46 ± 1.21  
G3: 5.99 ± 1.86  
G4: 6.72 ± 2.30  
G5: 7.22 ± 2.73 |          | Ceramic brackets:  
G1: 20.06 ± 2.34  
G2: 25.01 ± 4.45  
G3: 21.62 ± 6.48  
G4: 23.18 ± 6.51  
G5: 29.22 ± 8.20 |          | Not mentioned |                                       |
|                       |        |                                                        |                           |                     |         |               |                     |                                     |
| Mehmeti et al.         | 20     | G1) Sandblasting                                       | Transbond XT primer + Transbond XT light cure composite | G1: Metal brackets  
G2) Sandblasting + Metal/Zirconia primer |         | G2: Poly-cry stalline ceramic brackets | Waterbath for 24 hrs. | G1: 7.35 ± 3.41  
G2: 4.66 ± 1.78 |          | Not done          |                                      |                     |                       |                                    |
|                       |        |                                                        |                           |                     |         |               |                     |                                     |
|                       |        | 37% phosphoric acid for 120s                           |                           |                     |         |               |                     |                                     |
|                       |        |                                                        |                           |                     |         |               |                     |                                     |
|                       |        | G1) Sandblasting                                       | Transbond XT primer + Transbond XT light cure composite | G1: Metal brackets  
G2) Sandblasting + Metal/Zirconia primer |         | G2: Poly-cry stalline ceramic brackets | Waterbath for 24 hrs. | G1: 7.35 ± 3.41  
G2: 4.66 ± 1.78 |          | Not done          |                                      |                     |                       |                                    |
|                       |        |                                                        |                           |                     |         |               |                     |                                     |
|                       |        | 37ºC distilled water for 24 hrs.                       | Ceramic brackets          |                     |         |               |                     |                                     |
|                       |        |                                                        |                           |                     |         |               |                     |                                     |
|                       |        | G1) Sandblasting                                       | Transbond XT primer + Transbond XT light cure composite | G1: Mandibular anterior metal brackets  
G2) Sandblasting + Metal/Zirconia primer |         | G2: 100% relative humidity for 7 days | 2,000 cycles between 5º-55ºC for 1 minute | G1: 11.4 ± 5.8  
G2: 21.6 ± 3.3  
G3: 22.9 ± 6.5  
G4: 19.7 ± 4.1  
G5: 20.5 ± 5.4  
G6: 24.2 ± 2.8 | Thermocycled:  
G1: 13.7 ± 5.0  
G2: 20 ± 4.9  
G3: 22.5 ± 6.9  
G4: 25 ± 5  
G5: 24.1 ± 3.5  
G6: 26.2 ± 3.1 |                                      |                     |                       |                                    |
|                       |        |                                                        |                           |                     |         |               |                     |                                     |
|                       |        | G1) Sandblasting                                       | Transbond XT primer + Transbond XT light cure composite | G1: Mandibular anterior metal brackets  
G2) Sandblasting + Metal/Zirconia primer |         | G2: 100% relative humidity for 7 days | 2,000 cycles between 5º-55ºC for 1 minute | G1: 11.4 ± 5.8  
G2: 21.6 ± 3.3  
G3: 22.9 ± 6.5  
G4: 19.7 ± 4.1  
G5: 20.5 ± 5.4  
G6: 24.2 ± 2.8 | Thermocycled:  
G1: 13.7 ± 5.0  
G2: 20 ± 4.9  
G3: 22.5 ± 6.9  
G4: 25 ± 5  
G5: 24.1 ± 3.5  
G6: 26.2 ± 3.1 |                                      |                     |                       |                                    |
|                       |        |                                                        |                           |                     |         |               |                     |                                     |
### Table 2 - continuation: Data extraction.

| Study                                      | Sample | Surface treatment                                                                 | Adhesive                  | Brackets                | Storage                        | Thermocycling | Bond strength (MPa) |
|--------------------------------------------|--------|-----------------------------------------------------------------------------------|---------------------------|-------------------------|--------------------------------|---------------|---------------------|
| **Kim et al.**<sup>20</sup> (2017)        | 160    | G1) Sandblasting + ESPE-sil  
G2) Sandblasting + Alloy primer  
G3) Sandblasting + Clearfil ceramic primer  
G4) Sandblasting + Single bond universal primer  
G5) Tribochemical silica coating + ESPE-sil  
G6) Tribochemical silica coating + Alloy primer  
G7) Tribochemical silica coating + Clearfil ceramic primer  
G8) Tribochemical silica coating + Single bond universal primer | Transbond XT light cured composite | Maxillary central incisor metal brackets | Deionized water 37°C for 24 h | 5000 cycles between 5º-55ºC with 30s dwelling time | Non-thermocycled:  
G1: 6.6 ± 2.6  
G2: 15.9 ± 5.2  
G3: 13.1 ± 3.4  
G4: 16.7 ± 5.6  
G5: 7.9 ± 3.4  
G6: 17 ± 3.9  
G7: 15.9 ± 5.7  
G8: 19.4 ± 4.5 | Thermocycled:  
G1: 5.2 ± 1.4  
G2: 14.3 ± 2.9  
G3: 12.9 ± 4.3  
G4: 15.2 ± 5.3  
G5: 5.8 ± 1.6  
G6: 8.6 ± 1.7  
G7: 14.8 ± 3.9  
G8: 7.1 ± 0.9 |
| **Amer and Rayyan**<sup>13</sup> (2018)  | 60     | G1) No surface treatment  
G2) Sandblasting  
G3) Soflex disc | i) Clearfil ceramic primer + Panavia F 2.0 adhesive resin cement  
ii) Rely X U200 self adhesive resin cement | Lower second premolar metal brackets | 37°C distilled water for 24 hrs. | 500 cycles between 5º-55ºC with 30s dwelling time | Clearfil + Panavia F 2.0:  
G1: 0  
G2: 20.8 ± 4.8  
G3: 12.3 ± 2.8  
Rely X U200:  
G1: 0  
G2: 16.7 ± 4.6  
G3: 11.6 ± 3 |
| **Ihsan and Al-Dabagh**<sup>29</sup> (2017) | 40     | G1) Z prime plus primer  
G2) Sandblasting (Al<sub>2</sub>O<sub>3</sub>) + Z prime plus primer  
G3) Nd:YAG laser (0.888 W, 5s.) + Z-prime plus primer  
G4) Nd:YAG laser (0.444 W, 10s) + Z-prime plus primer | Light-cured composite | Central incisor sapphire brackets | 37°C distilled water for 24 hrs. | Not done | G1: 11.08 ± 1.96  
G2: 22.29 ± 1.18  
G3: 30.25 ± 2.31  
G4: 30.67 ± 2.33 |
| **Hosseini et al.**<sup>18</sup> (2016)  | 72     | G1) No treatment  
G2) Er:YAG laser 1.5 W  
G3) Er:YAG laser 2.5 W  
G4) Er:YAG laser 3 W  
G5) Sandblasting  
G6) Silane primer | Transbond XT light cure composite | Maxillary incisor metal brackets | 37°C distilled water for 24 hrs. | 500 cycles between 5º-55ºC with 30s dwelling time | G1: 0.31 ± 0.23  
G2: 0.51 ± 0.14  
G3: 1.11 ± 0.40  
G4: 3.32 ± 1.52  
G5: 9.50 ± 2.92  
G6: 3.88 ± 2.20 |
Table 2 - continuation: Data extraction.

| Study            | Sample | Surface treatment                                                                 | Adhesive            | Brackets                  | Storage               | Thermocycling                    | Bond strength (MPa) |
|------------------|--------|-----------------------------------------------------------------------------------|---------------------|---------------------------|------------------------|-----------------------------------|------------------|
| Lee et al. 22     | 40     | G1) Non-glazed + Sandblasting + Zirconia primer  
G2) Glazing + Sandblasting + etching + Zirconia primer  
G3) Glazing + sandblasting + etching + porcelain primer  
G4) Glazing + sandblasting + etching + zirconia primer + porcelain primer | Transbond XT light-cured composite | Mandibular incisor metal brackets | 37°C distilled water | 2,000 cycles between 5º - 55ºC with 30s dwelling time | G1: 13.7 ± 1.3  
G2: 3.7 ± 0.9  
G3: 16 ± 2.6  
G4: 14.4 ± 1.7 |
| Kwak et al. 21    | 70     | G1) Silicon carbide paper roughening  
G2) Diamond bur + Z-prime plus primer  
G3) Pumice + Monobond-S primer  
G4) 4% hydrofluoric acid + Monobond-S primer  
G5) Sandblasting (Al₂O₃) + Monobond-S primer  
G6) Sandblasting (Al₂O₃) + Z-prime plus primer  
G7) Sandblasting (SiO₂) + Monobond-S primer | Transbond XT light-cured composite resin | Mandibular incisor metal brackets | 37°C water for 24 hrs | 1,000 cycles between 5º - 55ºC | G1: 13.38 ± 2.57  
G2: 15.48 ± 3.15  
G3: 14.90 ± 2.75  
G4: 15.24 ± 3.36  
G5: 15.78 ± 2.39  
G6: 4.60 ± 1.08  
G7: 14.81 ± 2.91 |
| Yassaei et al. 25 | 72     | G1) 9.6% hydrofluoric acid + silane primer  
G2) Sandblasting (Al₂O₃) + silane primer  
G3) Er:YAG laser (1W) + silane primer  
G4) Er:YAG laser (2W) + silane primer | Light-cured composite resin | Metallic maxillary central incisor brackets | 37°C water for 24 hrs | 500 cycles between 5º - 55ºC with 30s dwelling time | G1: 5.8 ± 0.78  
G2: 7.8 ± 1.02  
G3: 6.8 ± 0.92  
G4: 6.9 ± 1.13 |
RISK OF BIAS

The methodological merits of the selected studies were assessed by both reviewers individually. The assessment tool was adapted from previous *in-vitro* systematic reviews and meta-analyses, judging on the following parameters: sample size calculation, presence of control group, use of materials according to the manufacturer’s instruction, standardized sample preparation, surface treatment and bonding done by the same operator, adequate description of thermocycling and the appropriate statistical analysis (i.e., reporting mean, standard deviation and *p*-values). Any of these parameters reported by the articles was ticked with “Y” (yes) for the particular section. In case any parameter was missing, was marked with an “N” (no). Articles reporting only one (1) to three (3) of the items were considered as having a high risk of bias; four (4) to five (5) items, as medium risk of bias; and six (6) to seven (7) items, as low risk of bias. Again, the interexaminer agreement was analyzed by Cohen’s kappa statistics, and the third reviewer’s opinion was requested in any event of disagreement.

RESULTS

LITERATURE SEARCH

A total of 109 studies was identified (Table 1). After the removal of the duplicates, 91 articles remained. Upon careful screening of the titles and abstracts, 48 articles were further excluded.
The kappa value for interexaminers agreement was $k = 0.816$ ($p < 0.001$). Forty three full-text articles were screened thoroughly for eligibility and 24 articles were excluded for valid reasons (Supplementary Table 1). Finally, 19 articles were selected for the review. The PRISMA flow diagram of the study selection procedure is presented in Figure 1.

**Supplementary table 1:** Reason for exclusion.

| Article                        | Reason for exclusion                                      |
|-------------------------------|-----------------------------------------------------------|
| Ahluwalia et al., 2013        | Zirconium surface was not included                        |
| Buyuk et al., 2018            | Zirconium surface was not included                        |
| Byeon et al., 2016            | Full-text article was not found                            |
| Di guida et al., 2019         | Zirconium surface was not included                        |
| Dong et al., 2016             | Full-text article was not found                            |
| Elsaka et al., 2016           | Zirconium surface was not included                        |
| Juntavee et al., 2018         | Zirconium surface was not included                        |
| Kawai et al., 2011            | Orthodontic brackets were not included                    |
| Kaya et al., 2019             | Zirconium surface was not included                        |
| Murthy et al., 2014           | Orthodontic brackets were not included                    |
| Soliman et al., 2018          | Zirconium surface was not included                        |
| Zhang et al., 2016            | Zirconium surface was not included                        |
| Priti et al., 2019            | Zirconium surface not included                            |
| Gardiner et al., 2019         | Orthodontic buccal tubes included, not brackets           |
| Mehta et al., 2016            | Shear bond strength not measured                          |
| Mirhashimi et al., 2020       | Shear bond strength in MPa units not measured             |
| Abuelenain et al., 2020       | Lithium silicate reinforced with zirconia                 |
| Ahluwalia et al., 2013        | Porcelain fused to zirconia crowns                        |
| Amer and Rayyan, 2018         | Glazed monolithic zirconia crowns                         |
| Bilic et al., 2013            | Porcelain fused to zirconia crowns                        |
| Franz et al., 2019            | Zirconium oxide sinter ceramics                           |
| Ismail and Sheikh, 2018       | Porcelain veneered zirconia crown                         |
| Oldham et al., 2019           | Lithium silicate infused with zirconia                    |
| Pouyanfar et al., 2019        | Y-TZP zirconia was not included                           |
Figure 1: Flow diagram of the study selection strategy.
QUALITATIVE ASSESSMENT

For the qualitative analysis, the inter-reviewers reliability of the extracted data was confirmed (k = 0.89, p < 0.001). Three types of brackets were studied. Metallic brackets were the most common; followed by the ceramic, and sapphire brackets. Both mechanical and chemical methods of surface treatment were identified on the Y-TZP zirconia surface. Mechanical means included lasers, sandblasting, polishing and soflex disc, silicon carbide paper, and diamond bur roughening. Chemically, acid etching (9.6% hydrofluoric acid, 37% phosphoric acid), application of primers, and universal adhesive were found. Sandblasting was the most found surface treatment. Two types of sandblasting were noticed: conventional (Al₂O₃) sandblasting and tribochemical silica (SiO₂) coated sandblasting. Sandblasting method differed between the studies as the variables like particle size (25μm - 110μm), pressure (0.14 MPa - 0.4 MPa), time (5 seconds - 20 seconds), and the distance (10mm - 20mm) were not homogeneous. Three types of lasers were utilized: erbium-doped yttrium aluminum garnet laser (Er:YAG), neodymium-doped yttrium aluminum garnet laser (Nd:YAG), and the femtosecond laser. Sandblastings and lasers were also combined with various primers and universal adhesive. Eight studies treated Y-TZP surface with sandblasting only; five studies combined sandblasting with silane primer; five studies combined sandblasting with MDP (methacryloyloxydecyl dihydrogen phosphate) primers; four studies combined
universal adhesive,\textsuperscript{2,19,20,27} three studies combined MDP containing silane primer,\textsuperscript{2,14,20} and two studies combined zirconia primer.\textsuperscript{22,27} Lasers were used alone in four studies,\textsuperscript{12,16-18} and as an adjunct with MDP primer and silane primer in one study each.\textsuperscript{18,25} One study also combined femtosecond laser and sandblasting to treat Y-TZP surface.\textsuperscript{17} Variability was observed in laser settings like power output (40 mW to 3 W); mean energy settings (50mJ to 300mJ), distance (60μm to 10mm), and the application time (5 seconds to 2 minutes). Except for two studies,\textsuperscript{18,28} no study was found to treat the Y-TZP surface solely with primers before orthodontic bonding. The trade names and chemical composition of the primers used to treat Y-TZP surface are listed in Table 3.

### Table 3: Primers used to treat Y-TZP surface.

| Primers                     | Trade name               | Chemical composition                                                                 |
|-----------------------------|--------------------------|--------------------------------------------------------------------------------------|
| Silane primer               | ESPE Sil, Rely X, Reliance porcelain conditioner | 3-TMSPMA, Ethanol                                                                   |
| MDP Primers                 | Z-PRIME Plus             | MDP, Ethanol                                                                         |
|                             | Zirconia liner           | MMA, 10-MDP, 4-methoxyphenol (HQME)                                                  |
|                             | Primer Alloy             | 6-(4-vinylbenzyl-n-propyl) amino-1,3,5-triazine-2,4 dithiol (VBATDT), 10-MDP, acetone |
| MDP containing Silane primer| Clearfil Ceramic Primer  | 10-MDP, 3-TMSPMA, Ethanol.                                                           |
| Universal adhesive          | Clearfil S3 Bond, Scotchbond universal adhesive, Single Bond Universal | 10-MDP, bis-GMA, HEMA, hydrophobic dimethacrylate, dl-camphorquinone, ethyl alcohol, water, silanated colloidal silica |
| Orthodontic primer          | Transbond XT adhesive primer | TEGMA, bis-GMA, triphenylantimony, 4-(dimethylamino)-benzeneethanol, dl-camphorquinone, ethyl alcohol, water, silanated colloidal silica |
| Zirconia primer             | Metal/Zirconia primer    | Tertiary butyl alcohol, methyl isobutyl ketone, phosphoric acid acrylate, benzoylperoxide. |

Abbreviations: 3-TMSPMA (3-trimethoxysilylpropyl methacrylate), 10-MDP (10-methacryloyloxydecyl dihydrogen phosphate), Bis-GMA (bisphenol-A-diglycidyl methacrylate), HEMA (hydroxyethyl methacrylate), TEGMA (triethylene glycol dimethacrylate), MMA (methyl methacrylate), HQME (hydroquinone monoethyl ether).
Two studies did not thermocycled their samples. Different protocols of thermocycling were observed between the studies; mostly at the range of 500-10,000 cycles, at 5 - 55°C temperature with dwell time of 20 to 30 seconds. The 37°C distilled water for 24 hours was the most common method of storage before bonding. Transbond XT® primer and light-curing composite were widely used as an adhesive.

Qualitative analyses of the included studies are detailed in Table 2.

**RISK OF BIAS**

Based on the criteria applied for the quality assessment of the selected studies; thirteen (13) studies scored medium risk of bias, three (3) studies scored low risk of bias, and the remaining three (3) studies scored high risk of bias. Sample size calculation was surprisingly absent (except for one selected study). Half of the studies had no control groups and surface treatment. Bonding was done by the same operator in only 47.4% of cases. The frequency of the rest of the parameters was sufficient (Fig 2).
Figure 2: Summary of the risk of bias of the included studies,
DISCUSSION

In the examined literature, different surface treatment protocols have been studied extensively regarding the adherence between the orthodontic brackets and the Y-TZP zirconia ceramics. Previously, several reviews on the ceramic surface conditioning and other testing parameters were published either with or without quantitative analysis. The reviews were neither of the specific types of ceramic surface nor on the effect of orthodontic brackets. Regarding mechanical testing protocols, the shear bond strength (SBS) test is the most popular method because it is less complicated and produces results with a smaller standard deviation. Therefore, the effect of surface treatment methods on the SBS of the orthodontic brackets, particularly on the Y-TZP zirconia ceramic surface, was reviewed.

In this review, 19 studies were included for in-depth analysis testing SBS of orthodontic brackets to Y-TZP surface bonded with light-cure resin/composites. Meta-analysis could not be performed due to the high heterogeneity of the included studies, limiting the study outcome. This high variability may be due to the variability in sample size, storage, thermocycling, sandblasting, different laser settings, bracket materials (i.e. metal, ceramic), bracket anatomy, and base design. Maxillary central incisor metallic bracket was mostly studied. On reviewing the studies that compared the
SBS between the metallic and the ceramic brackets, mixed outcomes were observed.\textsuperscript{15,17,26} A previously published research found that the ceramic brackets had greater bond strength to the Y-TZP surface than the metal brackets.\textsuperscript{17} On 37\% phosphoric acid etching, metallic brackets exhibited significantly better SBS than ceramic brackets.\textsuperscript{24} In a study, 37\% phosphoric acid was combined with silane primer to enhance the SBS of the ceramic brackets; but the result was not significant.\textsuperscript{26} In comparison to phosphoric acid etching, the hydrofluoric acid etching did not improve the SBS in both metallic and ceramic brackets.\textsuperscript{26} In fact, surface pre-treatment with hydrofluoric acid resulted in lower SBS of orthodontic brackets, in comparison to sandblasting, Er:YAG laser irradiation, and 37\% phosphoric acid etching.\textsuperscript{12,26} Due to the possibility of weakening the ceramic surface, the use of hydrofluoric acid was condemned.\textsuperscript{26} Both metallic and ceramic brackets exhibited higher SBS to the sandblasted and laser-irradiated surfaces in different studies. One study reported higher SBS of ceramic brackets on sandblasted, tribochemical silica-coated and femtosecond laser irradiated surfaces.\textsuperscript{17} Conversely, another study reported higher SBS of metallic brackets on the sandblasted and the Er:YAG laser-irradiated surface.\textsuperscript{15} Surprisingly, comparative analysis of the SBS of metal and ceramic brackets on Y-TZP surface treated by various primers could not be found.
Sandblasting was found as the most common surface treatment method among the included studies. It promotes mechanical bonding by creating surface irregularities through air abrasion, using either alumina or silica-coated alumina particles. The latter procedure exhibited greater SBS in many studies.\textsuperscript{12,19-21} The CoJet\textsuperscript{TM} system that applies silica-coated alumina particles not only abrades the ceramic surface, but also creates silica enriched outer surface favorable for silanization.\textsuperscript{6} Surface irregularities created by both of these particles were similar in previous studies.\textsuperscript{17,20} However, the surface free energy was greater in silica-coated sandblasting.\textsuperscript{19,20} Therefore, the additional application of primers promoting chemical adhesion might have contributed to the higher SBS. Following both forms of sandblasting, primers like silane, MDP, MDP containing silane primers or single-step universal adhesives were applied to optimize the SBS.\textsuperscript{2,4,19,20,22} The primers and universal adhesives that contain MDP are capable of chemically bond to zirconia. The bonding occurs between the phosphate ester of MDP and the hydroxyl groups over the zirconia surface.\textsuperscript{14} The silane primers had lower SBS in comparison to the universal bonding resin, MDP, or MDP containing silane primers, as they do not form a chemical bond with zirconia unless the surface is coated with silica.\textsuperscript{14,19,20}
Mechanical surface treatments such as sandblasting and lasers also have been studied.\textsuperscript{12,16-18,25,29} Lasers produce surface roughness by a process called ablation, which involves micro explosions and vaporization.\textsuperscript{6} Both Er:YAG and Nd:YAG laser irradiation of zirconia surface resulted in inferior SBS, compared to sandblasting.\textsuperscript{12,15,18,25} The Er:YAG lasers alone failed to achieve Reynolds’s optimal SBS range of 5.9 - 7.8 MPa.\textsuperscript{12,18,30} Yet, in combination with silane primer, the SBS was raised to 6.9 MPa.\textsuperscript{25} The additional chemical reaction and wetting ability of the silane may have contributed to this finding. Besides, at high power output (above 200 mJ) the laser generates high heat, which can be detrimental to the surrounding zirconia surface.\textsuperscript{31} The femtosecond lasers, at 200mW power output and 60\textmu m inter-groove distance, generated SBS (5.68 MPa) closer to the optimal level.\textsuperscript{15} In separate studies, the femtosecond laser-treated zirconia surface had better SBS compared to both alumina (Al\textsubscript{2}O\textsubscript{3}) and silica (SiO\textsubscript{2}) coated sandblasting.\textsuperscript{16,17} Better SBS was achieved when the femtosecond laser was combined with sandblasting, but not significantly greater than the femtosecond laser alone.\textsuperscript{17} Thereby, additional surface preparation as an adjunct to femtosecond laser can be avoided to save time, cost and patient discomfort. Besides, the laser has no reports of thermal damage due to surface irradiation.\textsuperscript{32}
Following thermocycling, there was a noticeable reduction in SBS irrespective of the surface pre-treatment methods.\textsuperscript{2,14,19,20} Biodegradation of the treated Y-TZP surface, bonded brackets, and adhesives may have contributed to this evidence. Hence, the assessment of the bond strength in a simulated clinical environment (i.e., \textit{in-vivo} experiment) is necessary. Thermocycling is an artificial aging procedure to test the long-term effect of bond strength. According to a study, 10,000 cycles of thermocycling are equivalent to one year of usage in the oral cavity.\textsuperscript{33} Application of MDP and MDP containing silane primers resulted in durable and optimal SBS on both forms of sandblasted Y-TZP, even after 10,000 cycles of thermocycling.\textsuperscript{2,20} Conversely, in the case of universal adhesives, the SBS was stable up to 2,000 cycles, but degraded significantly after 10,000 cycles.\textsuperscript{2,20,27} Among lasers, the effect of thermocycling on the Er:YAG and Nd:YAG laser irradiated surfaces were tested. The SBS on Er:YAG laser-treated surface was found to be just clinically acceptable within the range of 500-2,000 cycles.\textsuperscript{12,25} In the case of Nd:YAG laser, the SBS was below an acceptable level after thermocycling.\textsuperscript{12} Surprisingly, the effect of thermocycling on the femtosecond laser irradiation could not be found.
The validation risk of the bias tool utilized in this study could not be confirmed. This fact should be regarded as an important limitation of the study, but the contents of this quality assessment tool seemed to be more justifiable and relevant to the methodology of the selected studies. The absence of meta-analysis is another limitation reflecting the heterogeneity of the studies.

**CONCLUSION**

As this review is solely based on the qualitative analysis of the laboratory-based *in-vitro* findings, the results should be interpreted with caution. To answer the research question of this review more precisely, quantitative analysis is deemed necessary. Therefore, standardization of the study protocol is necessary. However, certain points may be advised, in light of this comprehensive review:

a) Hydrofluoric acid etching can be avoided to treat the Y-TZP surface, as it did not remarkably improve the SBS, considering the damage to the ceramic surface.
b) Mechanical pretreatments like sandblasting and lasers are useful, as they both improved the SBS of orthodontic brackets.

c) Tribochemical silica-coated sandblasting with the advantage of chemical adhesion resulted in greater SBS than conventional sandblasting.

d) Among lasers, the femtosecond laser can be suggested as the first choice; although the effect of thermocycling on this laser irradiated zirconia surface is unknown.

e) Use of primers, particularly the MDP and the MDP containing silane primers as an adjunct to the mechanical pretreatments may be justified. There is a concern over the longevity of the universal adhesive.
AUTHORS’ CONTRIBUTIONS

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