Study of the biomechanical behavior of the all ceramic dental crown

Michel Fages, DDS

Supervisors: Prof. Dr. Frédéric Cuisinier, DDS,PhD.
and Dr. Kinga Turzó, PhD.

UFR Odontologie, Université Montpellier I and
Department of Oral Biology and Experimental Dental Research,
Faculty of Dentistry, University of Szeged

Graduate School of Clinical Science
Research in Dental Medicine

Szeged

2013

List of abbreviations:

CAD/CAM : Computer Assisted Design/Computer Assisted Fabrication
SI: Speckle Interferometry
CCD Camera: Couple Charge Device Camera
DEJ: Dentin-Enamel-Junction
DCJ: Dentin-Ceramic-Junction
COF: Curvature Occlusal Face
TOC: Total Occlusal Convergence
SA: Shoulder Angulation

1.Introduction

Monolithic glass-ceramic crowns have a reputation for fracturing under occlusal force. This issue is described as one of the major problems of glass ceramic restorations, especially on posterior teeth.

However, authors (1) stated that "the dentin-bonded all-ceramic crowns might exhibit many favorable characteristics, including those of good aesthetics, marginal blending with gingival tissues and the ability to be placed on conservative preparations, which may minimize the risk of pulpal damage."

Despite this, the biomechanics of the reconstructed tooth with glass-ceramic and the role of complex prosthesis geometry and its interaction with other factors on damage initiation and propagation have yet to be well characterized.

If we take the natural tooth as a reference, we observe that the Dentin-Enamel Junction (DEJ) is the zone between two distinct calcified tissues that have very different biomechanical properties: enamel and dentin. Enamel is hard and brittle and envelops the softer dentin. In 2003 Magne and Belser (2) understood the interest in the DEJ and said: *"The fascinating properties of the DEJ must be a reference for the development of new dentin bonding agents that must restore the biomechanical integrity of the crown restored"*. Bonding agents must be selected very carefully because they determine not only the adhesion but also the ultimate strength of full-ceramic crowns; therefore, it is important to observe and compare the mechanical behavior of natural teeth and of the all-ceramic crowns glued on dentin.

A part of my study was an optical study by means of Speckle Interferometry (SI), targeting the comparison of the mechanical behavior of the DEJ and the Dentin Ceramic Junction (DCJ). In this part, the behavior of a natural tooth and a monolithic glass ceramic reconstruction under loading was observed. To the best of our knowledge, our study is the first to investigate the behavior of the enamel-dentin junction under duress in comparison with the bonded joint dento-prosthetic, ceramic-dentin junction.

As monolithic glass-ceramic crowns have a reputation for fracturing during use, the second aim of my study was to determine the effect of geometric features on the mechanical response of monolithic glass ceramic peripheral crowns manufactured by the CAD/CAM system and to identify the role-played by several geometric factors.

The goal was to prepare a shape in accordance with the principles of biomechanics and of the accommodation constraints of the DEJ. For this aim, we developed an original method for assessing the mechanical behavior of full-ceramic peripheral crowns based on the use of Computer Assisted Design (CAD) and Computerized Assisted Manufactured (CAM) systems. CAD/CAM enables the manufacturing of a series of samples and sample-holders that are perfectly identical, reproducible and adapted to dental prosthetic tests.

From there, we must find the balance between the natural tooth preparation, the material of reconstruction, the fixation material and the nature of the load in what is known as "the biomechanical concept".

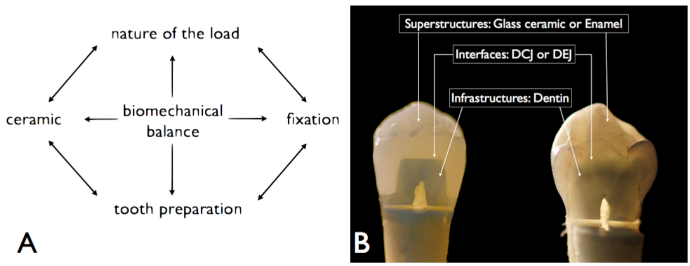


Fig. 1. A) The biomechanical concept of tooth restoration (own picture). B) The ideal biomechanical postulate is to have reduced interfaces and for the materials for a prosthetic reconstruction to obtain the same behavior as the natural tooth. In this case, the ceramic replaces enamel, and the Dentin-Ceramic-Junction (DCJ) replaces the Dentin-Enamel-Junction (DEJ).

2. Biomechanical study: a comparison of the mechanical behavior of dentin enamel and dentin ceramic junctions by Speckle Interferometry (SI)

In this study, we compared for the first time the mechanical behavior of the natural tooth and a prosthetic crown manufactured with a CAD-CAM system using SI.

2.1. SI Principle

When a laser beam illuminates a surface that is not highly polished, an image (interference pattern) related to the structure of the surface itself, the speckle, is produced as a result (3). The speckle from the object then interferes on the optical sensor with a reference beam (object speckle or smooth beam) to detect the phase of the light relative to the position and shape of the object, which then creates specklegrams. The subtraction of two specklegrams at different loads enables an analysis of the changes in the surface (by deformation example) from interference fringes that appear.

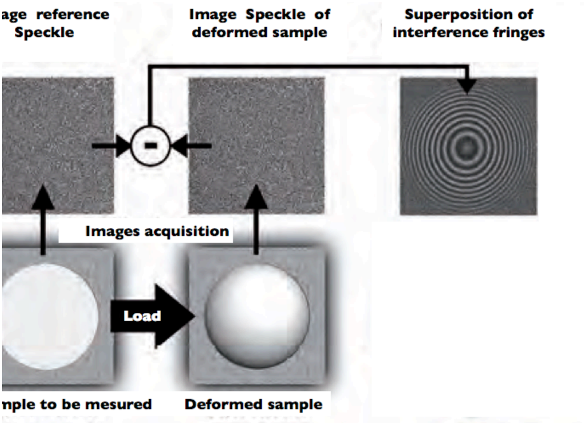


Fig. 2. The process of Speckle Interferometry.

2.2. Materials and methods

We developed a complete apparatus that enabled the study of the compressive mechanical behavior of the concerned teeth by SI.

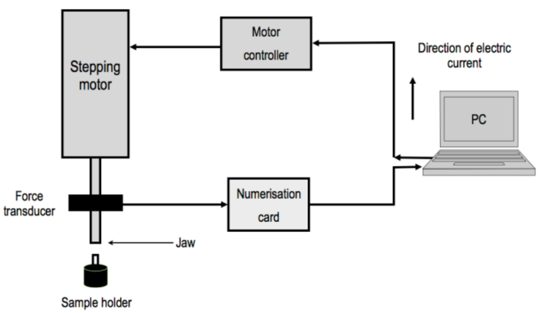


Fig. 3. Mechanical set-up diagram.

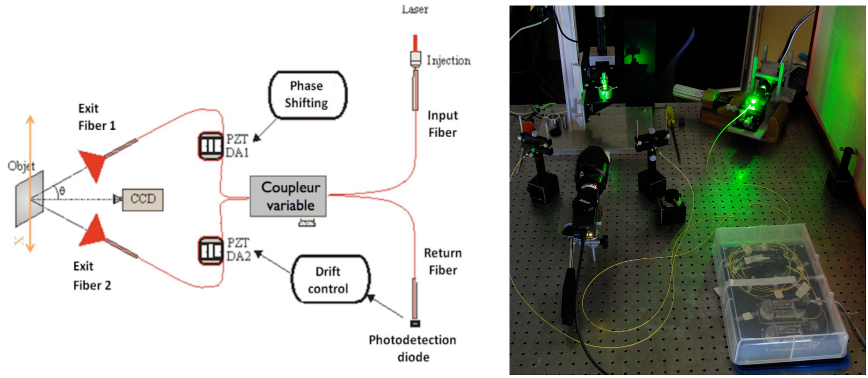


Fig. 4. Speckle Interferometry set-up diagram and plan speckle interferometer

This study was the first time that the CAD/CAM was used to make clone samples for experiments. The prosthetic crowns were manufactured with a prosthodontic chairside CAD-CAM system from an optical print (4). The software allowed for a perfect clone of the reference sample to be created. The necessary space for the glue was also entered with ideal values. This duplication process yields two samples with identical anatomy for further processing.

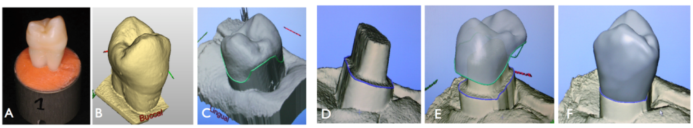


Fig. 5. Cloning process: A) intact natural crown sample, B) optical print, C) shaping, D) optical print of the second tooth prepared to receive the prosthetic, E) adaptation of the shaping on the prepared tooth, F) CAD finished, CAM ready.

To obtain reliable and reproducible measurements, we considered the half-cut crowns because this approach allows for the observation of the behavior of the DEJ and the DCJ in the observation plane either far away or very close to the loading zone. This approach has major advantages and represents another originality of this study.

Fig. 6. Natural tooth and clone before and after the vertical cut.

The compression test consisted of an initial increase in the load until the whole set-up was well established at approximately 120 N. Then, the force was decreased to the minimum contact and was slightly enhanced to generate live fringe maps. The same loads were applied to the natural tooth and to the prosthetic crown samples to enable comparisons of their respective compressive behaviors. A CCD Camera is recording at the sample surfaces the interferences of the two illumination beans coming from the output optical fibers.

2.3. Results and discussion

On SI images, the interfaces appear distinctly along their entire lengths, thus showing the complete loading (from 35.5 N for the DEJ on the natural tooth and from 36 N for the prosthetic crown). In this chapter, we have selected typical photos and results to avoid overloading this section.

From all of the screenshots, different images were chosen for use in computing the displacement maps. We selected several screenshots and two of them are presented below.

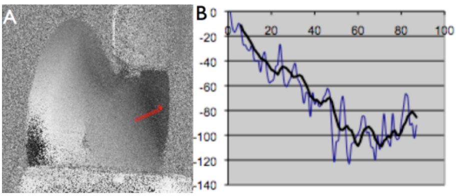


Fig.7. Natural tooth behavior at a load of 39.21 N, ΔF = 1.18 N, N ref: 40.39 N.
A) SI image: six red equal parallel lines are defined across the DEJ. B) Displacement curves: The blue curve represents displacement values along one of the six red lines. The black curve is the mean value fitting of the 6 blue curves. The displacement was approximately 95 nm.

To calculate the displacement value, six red equal parallel lines were defined across the DEJ. The displacement was calculated as the average value of the six-stacked profiles. In Fig 7 the black curve is the mean value fitting of the blue curve values along the six paths, and the blue curve is one of the six displacement curves. The mean relative displacement between the dentin and the enamel was approximately 20 nm for loads between 39.21 N and 40.39 N (ΔF = 1.18 N).

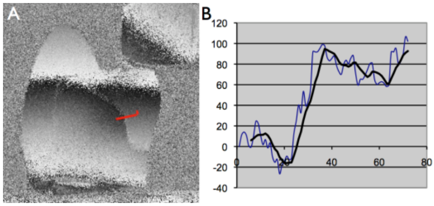


Fig.8. Prosthetic crown behavior under a load of 72.85 N, ΔF=10 N, N ref: 82.85 N.

In Fig. 8, to evaluate the displacement values, six equal parallel straight paths were defined in the region of interest across the DCJ in the palatine zone in front of the loading point (Fig 8) In Fig 8 the displacement is displayed as the average value of the six-stacked profiles. The black curve is the median value fitting of the blue curve values. In this case, the relative displacement was approximately 95 nm for loads between 82.8 N and 72.8 N (ΔF = 10 N).

The first interpretation confirms that the enamel bulk and the ceramic cap will move slightly under loading as rigid bodies. However, the mechanical response was different for the same applied loading force, and the displacement was greater for ceramic than for enamel. For the prosthetic samples an iso-displacement is confirmed in SI pictures (43 nm and 95 nm). This behavior demonstrates the accommodation strength of the DCJ and confirms its protective role for the ceramic caps. Moreover, we emphasize that the displacement of the crown, whether enamel or ceramic, is different if the measurement area is far from or close to the loading zone. In each case, the most important displacements were located opposite to the load. The gray levels also showed a displacement of the opposite cuspid but of a smaller magnitude.

Above a certain load (117.4 N for the prosthetic crown and 82.6 N for the natural tooth), the SI images showed that the DEJ and the DCJ could not be clearly observed (Fig. 9.). The interfaces could no longer accommodate the loading stress.

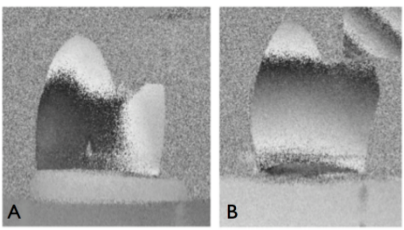


Fig. 9. On the natural tooth (A) and the prosthetic sample (B) the dentin-enamel junction (DEJ) and the dentin ceramic junction (DCJ) cannot clearly be observed.

We have demonstrated a similar behavior for the DCJ and the DEJ. We believe these zones are crucial for the stress resistance of the crown structure, whether natural or prosthetic.

3. Mechanical study: Design influence for tooth preparation receding a monolithic ceramic crown

3.1. Statement of the problem

To replace the enamel by a ceramic and the DEJ by a bonded joint may seem problematic. Indeed it is because the relationship between the physical properties of these materials and the geometry of the support has not really been studied. In this part of study various parameters that can improve the strength of monolithic ceramic reconstructions are analyzed, which constitutes a new approach in this field.

3.2. Materials and methods

The sample is a superstructure (ceramic cap) adhesively glued on aluminum-milled infrastructure representing the tooth.

For the validity of the study we produced different samples with specific characteristics using CAD/CAM systems only. CAD was firstly used to model an infrastructure, which represents the tooth preparation (5). We determined a basic preparation, for which the value of the three factors will vary, thanks to the CAD system. Those factors are: the **TOC** (Total Occlusal Convergence), the **COF** (Curvature of the Occlusal Face) and the **SA** (Shoulder Angulation). From the CAD and for each shape, five infrastructures were milled in aluminum barrel.

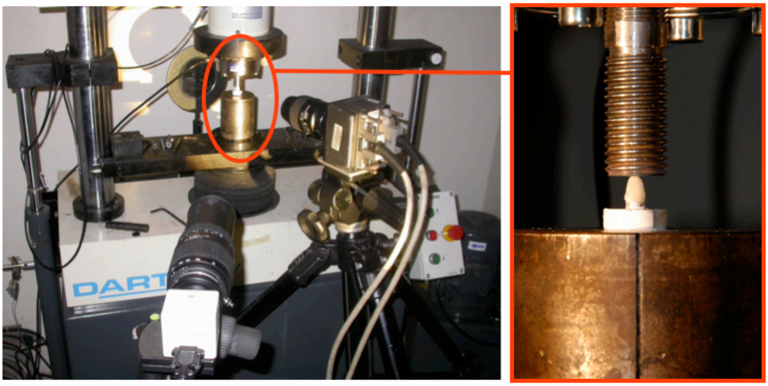
		S1	S2	S3	S4	S5	S6
Series							
Fixed values	D1 (mm)	6	6	6	6	6	6
	D2 (mm)	4.2	4.2	4.2	4.2	4.2	4.2
	H1 (mm)	9	9	9	9	9	9
	L1 (mm)	0.9	0.9	0.9	0.9	0.9	0.9
Variables values	TOC (°)	21	7	7	21	7	7
	COF (°)	1.3	1.9	1.9	1.2	0	0
	SA (°)	45	45	90	90	90	45

Table. I. The six different infrastructures and their characteristics.

Ceramic superstructures were produced with the Cerec AC CAD/CAM system and milled from Vita Mark II ceramic blocks. One optical imprint was taken for each shape. Five superstructures were milled from the same optical print. A total of 30 ceramics caps were milled (5 samples for 6 series). Then ceramic caps are glued on aluminum infrastructures.

Using a mechanical press, samples were submitted to a compressive loading until rupture. Mechanical tests were monitored, leading to interesting graphs, and the rupture force values were collected. Results were established in order to find out the strongest design and to analyze the corresponding favorable parameters.

Fig. 42. Mechanical testing system and **s**pecimen between jaws.



3.3. Results

Results of this study are summarized in Table II, III and Fig. 11.

Series	S1	S2	S3	S4	S5	S6
						
Mean rupture (kN)	1.048	1.255	1.314	1.744	1.884	1.902
SD	0.057	0.099	0.150	0.256	0.344	0.252
Dispersion (%)	4	9	11	14	18	13

Table II. Mean value of the ultimate force, Standard Deviation (SD) and dispersion for each series.

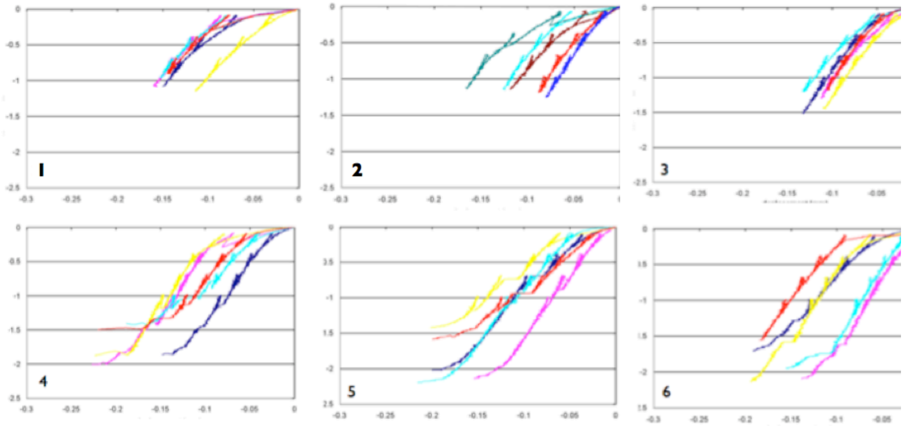


Table III. Force-displacement curves for each series.

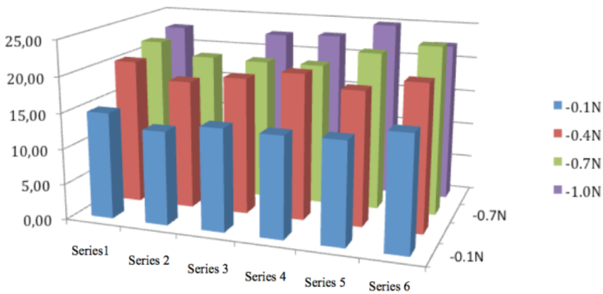


Fig. 11. Responses to stress exhibited by the samples; the evolution of apparent stiffness (kN/mm) for different loading force levels was calculated.

3.4. Discussion

3.4.1. Efficiency of the method

The results presented in this study: low dispersion of strength results and reproducibility of the sample stiffness, highlight the interest of the CAD/CAM construction and confirms that this method is efficient for creating all types of models to obtain results with a minimum dispersion, which is due to the reduction of operator-dependent steps and the suppression of the material dependence of the conventional prosthetic chain.

3.4.2. Effect of the three variables

- *The effect of Total Occlusal Convergence (TOC)*

The results obtained in our study tend to confirm the hypothesis that the more the convergence is pronounced, the sooner the fracture appears. The explanation of this result is that a high TOC value may favor the "opening" of the ceramic during the application of the load, leading to tensile stresses into its internal area**.** Fracture may start from the inside of the crown and propagate to its outside. The weakening induced by tensile stressed areas increases with high TOC angles.

- *The effect of the Curvature of the Occlusal Face (COF)*

The two best performances were recorded for infrastructures with a flat occlusal surface (0° COF). This "efficiency" seems to be confirmed by the large difference in results between S2 series and S6 (52%) where only the COF is different. The difference is very low between S5 and S6 series, highlighting its role in load distribution. For preparations with flat occlusal face, because the loading force is more evenly distributed, thus lowering contact stress and leading to higher rupture force values. The stress distribution is harmonious and significant and decreases loads transfer on axial walls.

- *The effect of the Shoulder Angulation (SA)*

Its influence is evident by comparing S1/S3 series and S2/S4. This is less significant for series S5 and S6 because of the role of the COF at 0°. There is only 1% of difference between those two shapes, and the only difference is the SA. But this does not mean that the SA has no influence. Indeed, if we compare S1 and S3 the only difference is the SA and the difference of rupture is 24.8%. If the occlusal surface is rounded and /or wall more convergent then the role of SA appears.

A 90° cervical shoulder acts as a "lock" at the opening of the ceramic, and increases its tensile strength by 25% (S1/S3) to 40% (S3/S4).

- *Parameter combination (TOC, COF, SA)*

The results show that the above discussed three factors TOC, SA, COF, are individually influencing the strength of ceramics, but beside this, their combination is also important/relevant. This is well illustrated comparing S2/S4 and S5/S6 series.

For S4/S5 the only difference is the SA and the difference of the rupture force is only 0.5%. According to this result it seems that SA has no influence. For S2/S4 the only difference is the SA and the difference of resistance to rupture is 40%. The TOC is the same for S2, S4, S5, and S6 but between S2/S4 and S5/S6 the difference is the COF. We can conclude that if the COF is 0°, SA has no influence, but if the COF is rounded SA has an important influence. Other examples also support the combined effect of these parameters.

4. Summary of the thesis

In contrast to prosthetic reconstructions with frameworks (II), we chose to work on monolithic glued ceramics prosthetic restorations in accordance with biomimetic concepts.

We have compared for the first time the mechanical behavior of the natural tooth and a prosthetic crown manufactured with a CAD-CAM system using Speckle Interferometry (I). The biomechanical study comparing the mechanical behavior of dentin enamel and dentin ceramic junctions by SI provided important new and reliable information's. Our Speckle Interferometry study proved that the enamel tooth cap moves as a rigid body under loading. The results demonstrate a similar behavior for the prosthetic crown tooth realized with biomimetic concept (III).

This is the first study that used the CAD / CAM system to produce reference samples and clones of the reference samples. This method will allow further comparative studies of great interest in prosthetic dentistry.

The replacement of the enamel by a ceramic and the DEJ by a bonded joint represents an important and general problem in dentistry. The mechanical study on the influence of the design for tooth preparation receding a monolithic ceramic crown presented in this thesis provided a new approach in this field.

Our study demonstrated that it remains necessary to know the most favorable geometric shapes to bond all ceramic crown on teeth completely prepared (IV). It is also the first time that we have individualized different geometrical factors affecting the strength of the glass ceramic, this again thanks to CAD/ CAM. The results show that three factors TOC, SA, COF, have individually an influence on the strength of ceramics and more accurately their combination.

The main conclusion of our study is that dental preparations should no longer be considered as simple geometric shapes optimizing the "retention-stabilization.". They must understand as architectural constructions favorably distributing load transfers, in line with new materials for reconstruction and fixing bio-mimetic vocation.

5. Acknowledgments

My first acknowledgements go for Prof.Nagy Katalin, Dean of the Department of Dentistry and Oral Surgery at University of Szeged, and Prof. Zoltan Rakonczay (University of Szeged, Department of Dentistry and Oral Surgery) who accepted that I defend my thesis in the Dental School of Szeged.
Foremost I would like to thank to the two co-directors of my thesis: Dr. Kinga Turzó (University of Szeged, Department of Dentistry and Oral Surgery) for her constant help support, and her wise advices and to Prof. Frederic Cuisinier (Université Montpellier I, UFR Odontologie, EA 4203) for having always supported me, and trusted in my works.

I would like to thank Prof. Csilla Gergely (Université Montpellier II, Laboratoire Charles Coulomb), and Prof. Jacques Margerit (Université Montpellier I, UFR Odontologie, Prosthetic Department) for their support throughout my work.
I am grateful to Pierre Slangen, Stéphane Corn, Patrick Ienny and all the whole team of Mechanics Laboratory of the "Ecole des Mînes d'Alès" for their friendly involvement in my work.
I also thank to my wife Ketsila and my children Anoussone and Guillaume to their patience and their support.

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7. Publications related to the thesis:

I. Slangen P, Corn S, **Fages M**, Cuisinier FJG: Prosthodontic crown mechanical integrity study using Speckle Interferometry. *Fringe* 2009, 6th International Workshop on Advanced Optical Metrology 1st Edition 2009: 734-738.
(Book chapter)

II. Durand JC, Jacquot B, Salehi H, **Fages M**, Margerit J, Cuisinier FJG: Confocal Raman microscopic analysis of the interface zirconia/feldspathic ceramic interface. *Dent Mater* 2012 Jun; 28(6): 661-71.
(IF: 3.135)

III. Fages M, Slangen P, Raynal J, Cornb S, Turzo K, Margerit J, Cuisinier FJ:

Comparative mechanical behavior of dentin enamel and dentin ceramic junctions assessed by speckle interferometry (SI). *Dent Mater* 28(10): e229-38
(IF: 3,135)

IV. Fages M, Corn S, Ienny P, Raynal J, Slangen P, Margerit J, Cuisinier FJG: CAD/CAM: A new « tailor made » methodology for assessing mechanical behavior of full ceramic crowns. *(under review)*