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# A Computer-Aided Tool to Predict Dental Crown Prosthesis Surface Integrity after Milling

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**ABSTRACT**

The roughness of dental prostheses surfaces, manufactured by CAD/CAM, is one of the major components of surface integrity (SI) to insure clinical success. This article aims at evaluating and quantifying the influence of the milling process characteristics on the roughness. First, the experimental results emphasize an influence of the tool grit size, the tool/prosthesis inclination and the biomaterials used on roughness. Then, based on these results, the definition of performance indicators for multi-physical and multi-indicator SI evaluation are proposed and implemented on a computer-aided tool to predict roughness. The use of this tool might help to proceed a topological decomposition of the crown to better respect the prosthetic specifications and to provide valuable assistance to the practitioner or the laboratory technician.

**Keywords:** dental CAD/CAM, prosthesis, surface integrity, roughness predictive tool.
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## 1 INTRODUCTION

Various pathologies (caries, fractures, fluorosis, and hypo-mineralization of enamel) lead to the rehabilitation of teeth with dental prostheses. Nowadays, prostheses can be manufactured from prefabricated biomaterial raw blocks, which are milled with a computer-aided design/computer-aided manufacturing (CAD/CAM) numerical chain [5]. The major challenge in restorative dentistry is to manufacture dental crown prostheses which are able to rehabilitate the tooth in order to fulfil functional performance and aesthetic requirements. Main clinical requirements are mechanical prosthesis retention, prosthesis and antagonist wear, non-plaque retention, aesthetic, and lifetime.

The milling process generates a characteristic signature on the prosthesis shape called surface integrity (SI) [3],[6],[7]. The residual SI after milling, not well understood in restorative dentistry, influences several requirements of the prosthesis surface such as aesthetics, biological response and mechanical behavior. Moreover, for each requirement, a specific SI might be manufactured in different anatomical area of the prosthesis. The concept of SI represents a new and preferential approach to characterize the surface and sub-surface properties regard to the functional requirement of prosthesis. SI analysis provides a comprehensive evaluation of the surface and its impact on the performance of the prosthesis [4]. The main difficulty for prosthesis manufacturers is to integrate the different expected SI during CAM process and particularly to choose the milling process parameters in accordance with prosthesis functionalities. The generation of a desired SI is still an iterative process based on experimental results capitalization. This inverse problem shall be addressed by a new approach focusing on the prediction of the milling process signature on the CAD model of the prosthesis shape. The concept of process signature, which aggregate information on surface modifications caused by the milling to which a material is subjected to, on different levels of scale, is a promising strategy to achieve a knowledge-based solution of the inverse SI problem [2]. This paper aims at providing a computer-aided tool to help prosthesis manufacturers to choose milling process parameters according to the expected SI after milling. Since roughness is a SI fundamental component of the prosthesis functionalities characterization, SI study is focused on roughness in this paper.

## 2 MATERIEL AND METHODS

### 2.1 Prosthesis Shape Topological Analysis

First, a topological analysis of 16 typical crown shapes is performed. This analysis is based on 3 axes milling constrains (Fig. 1a). Indeed, in dental office the most used milling machine kinematic is 3 axes. When milling, the contact area (size and position) between the tool and the crown can change from it tip to it flank, and inversely, according to the prosthesis shape manufactured. These contact variations introduce residual roughness variations along the crown shape. The contact simulation is implemented in Matlab software through a PLY format map of the tool/prosthesis contact (Fig. 1b) based on the STL model of the prosthesis. According to the contact map the more representative contact surface types between the tool and the crown surface are highlighted (Fig. 1c).

### 2.2 Milling Experiments

Specific milling experiments are performed according to 3 more-representative contact surfaces found in the topological analysis. Eight tool/biomaterial couples are included in the experiments: 2 milling tools (Cerec pointed bur and Lyra bur) and 4 significant biomaterials indicated for crown restoration (3M Lava Ultimate, Vita Mark II, Vita Enamic, Dentsply Celtra Duo). The 8 couples are tested at 4 different feed rates (1000, 2000, 3000, and 4800 mm/min). A 4-axes dental milling center (Lyra prototype; GACD SASU) is used to perform the tests. This milling machine is representative of those used in dental office. The fourth rotary axis is used to manage the inclination angle between the tool axis and the crown surface. The other machining parameters are fixed. The volume of material removed on each sample is 37.5 $mm^3$. Its associated dimensions are defined along the 3 linear axes of the milling machine in order to obtain values representative of the machining conditions used in dental office. A depth of 0.5 mm following $\vec{y}$ is retained, which corresponds to a radial step with a 90° inclination angle and a cutting depth for the 2 other orientations (0° and 60°). The 15 mm length following $\vec{x}$ (maximum length possible in a CAD / CAM block) adopted allows to reach the programmed feed rate. A distance of 5 mm following $\vec{z}$, corresponding to the cutting depth with a 90° inclination angle is retained. The planar surface (5x15 $mm^2$) is swept all at once with the 90° inclination angle. Fifty round-trips at 0° and 60 ° inclination angles, with a radial step of 0.1 mm, are necessary. The milling center is fitted with a spindle speed of 60 000 RPM. The milling machine is warmed up before milling. Coolant is sprayed on the tool-material contact zone.

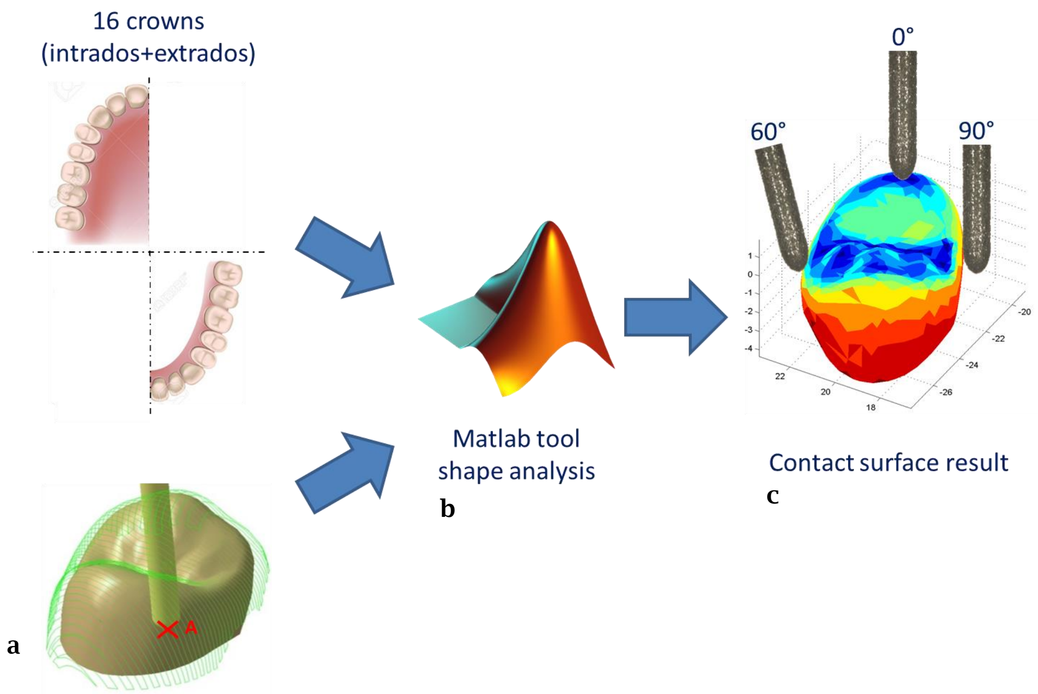


**Figure 1**: Topological decomposition synopsis. (a) 16 crowns shapes milled. (b) Matlab tool shape analysis. (c) Contact surface results.

### 2.3 Roughness Measurements Capitalization

For each 96 configurations the roughness is evaluated. Two- and 3-dimensional (2D and 3D) roughnesses are measured with a focal variation device (InfiniteFocus; Alicona Imaging GmbH). The 2D roughness profiles are recorded perpendicularly to the feed rate direction. Three profiles (approximately 1 mm in length) per specimen are recorded in the middle of the milled surface. The 2D roughness parameters determined are Ra (average roughness of profile), Rt (maximum peak to valley height of roughness profile), and Rz (mean peak to valley height of roughness profile). Three-dimensional roughness criteria are recorded on a 0.8×1 $mm^2$ planar surface. Two surfaces, in the middle of the milled areas, per specimen are recorded. In line with the NF EN 623-4 standard [1], aberrant points are excluded from the area. The 3D roughness parameters determined are Sa (average height of selected area), Sz (maximum valley depth of selected area), and Sq (root-mean-square height of selected area). Then, the mean and the standard deviation (SD) of each roughness parameters are calculated and saved in a data basis associated to the tool implemented in Matlab. Thus, prediction maps, implemented with a PLY file format, according to the tool-biomaterial couple, and the contact between the tool and the prosthesis shape, can be generated to predict residual roughness based on experimental results.

### 2.4 Performance Indicators

Independent roughness parameters and their results are not sufficient for evaluating final SI of prosthesis. To give an overall and reliable view and to assess SI by comparison to the clinically desired SI, 2 performance indicators are introduced. The two purposes of these 2 performance indicators are: (1) Allow prediction of SI (or one of its components, such as roughness) before CAD/CAM machining.

Prediction is made possible by the capitalization of previous machining test results. This offers the possibility of simulating several machining conditions to target the optimal SI that best meets the expected clinical functions, without wasting time. (2) Allow a global evaluation of the SI (or one of its components, such as roughness) obtained after machining by CAD/CAM without independent analysis of (roughness) parameters. Thereby, a comparison/improvement of SI obtained under different machining conditions can be done.

The first performance indicator is a weighted relative mean performance indicator named MSI (Mean Surface Integrity). MSI performance indicator, based on the calculation of the average, is from a mathematical point of view, a roughness position indicator. The second is a weighted relative standard deviation performance indicator named SISD (Surface Integrity Standard Deviation). SISD performance indicator, based on the calculation of the standard deviation, is from a mathematical point of view, a roughness range indicator. The 2 performance indicators do not provide the same type of information about shape residual roughness. They are complementary and cannot substitute each other. First of all, to compute these performance indicators, a set of the most relevant 2D and/or 3D roughness indicators is selected. A wise choice of this set of roughness indicators must be done to better represent the prosthetic functionalities expressed in the clinical specifications. A weight coefficient $\alpha_j$ (j: index relating to the considered roughness indicator) is then attributed to each selected indicator. The sum of these weight coefficients is defined to be equal to 1 ($\sum\alpha_j=1$). The measured values of the selected roughness indicators are then compared with expected those of the clinical specifications. This comparison, then results in the calculation for each surface integrity indicator, is the relative difference ($\Delta indicator_j$) between the expected indicator and the calculated indicator (measured or predicted measurements) Eqn. (2.1).

$$\Delta indicator_j = \frac{|expected\ indicator_j - calculed\ indicator_j|}{expected\ indicator_j} \quad (2.1)$$

Then, the first performance indicator MSI is given by Eqn. (2.2).

$$MSI = \sum_{j=1}^{j=r} \alpha_j \left(\Delta indicator_j\right) \quad (2.2)$$

Where: $\alpha_j$: weight coefficient for the indicator j.
r: number of selected indicators.

The second performance indicator SISD is given by Eqn. (2.3).

$$SISD = \sqrt{\sum_{j=1}^{j=r} \alpha_j \left(\Delta indicator_j - MSI\right)^2} \quad (2.3)$$

Where: $\alpha_j$: weight coefficient for the indicator j.
r: number of selected indicators.

Since a performance indicator is based on a relative difference, an optimal surface integrity (corresponding exactly to the clinical specifications) is therefore characterized by the two null performance indicators. Failing to reach the value of zero, the closer the performance indicators are to zero, the closer the surface integrity is optimal. The performance indicators are locally computed among the shape according to (1) the gap between the milling SI experiments results and the clinically desired SI, (2) the inclination angle between the tool axis and the surface, and (3) the tool-biomaterial couple (including the feed rate). The MSI and SISD are used to generate SI performance maps in PLY file format according to the prosthesis shape.

## 3 RESULTS AND DISCUSSION

The 16 crowns topological decomposition results reveal that inclination angles of 0°, 60° and 90° between the tool axis and the crown surface are the 3 more-representative orientation of the contact surfaces. The 90° inclination angle is the most used to mill a crown (19.2%) and is located on peripheral areas. On these areas main clinical functions concern the non-dental plaque growth. Located around the cusps, 60° is the second most used inclination angle (10%). The 0° inclination angle is clinically significant because of the occlusal contact and wears which occur on these areas.

### 3.1 Roughness

Measurements show that 2D and 3D roughness seem not to be dependent of feed rate. The process signature generated by the tool is anisotropic for 90° and 60° inclination angle and isotropic for the 0° inclination angle. The experimentations results show that the roughest surfaces are obtained with a 90° inclination angle (Ra=2.45 to 6.08 µm, Rt=12.88 to 29.2 µm, Rz=7.84 to 16.04 µm, Sa=1.776 to 3.49 µm, Sq= 2.23 to 4.32 µm, Sz=17.456 to 36.68 µm), and the smoothest surfaces with a 0° inclination angle (Ra=0.61 to 1.657 µm, Rt=3.3 to 6.68 µm, Rz=1.982 to 5.027 µm, Sa=0.505 to 1.326 µm, Sq=0.655 to 1.713 µm, Sz=7.03 to 16.4 µm). For the same biomaterial, a relationship can be established between Ra or Sa roughness parameters and the inclination angle. Indeed, Ra and Sa parameters increase when the inclination angle changes from 0° (example for Enamic/Lyra couple: Ra=0.719 µm, Sa=0.687 µm) to 60° (example for Enamic/Lyra couple: Ra=4.22 µm, Sa=3.12 µm) then from 60° to 90° (example for Enamic/Lyra couple: Ra=6.07 µm, Sa=3.49 µm). With a 90° inclination angle, on hard biomaterials (Vita Mark II Ra=2.44 to 4.87 µm, Sa=1.77 to 2.7 µm and Dentsply Celtra Duo Ra=2.67 to 4.71 µm Sa=2.008 to 2.83 µm) the roughness is lower. At the contrary, on soft biomaterials (3M Lava Ultimate (Ra=2.83 to 5.89 µm, Sa=2.23 to 2.96 µm and Vita Enamic Ra=2.63 to 6.07 µm, Sa=1.94 to 3.49 µm) the roughness is higher. With a 0° inclination angle the reverse phenomenon occurs. The hardest biomaterials (Vita Mark II Ra= 0.88 to 0.91 µm, Sa=0.77 to 0.85 µm and Dentsply Celtra Duo Ra= 1.30 to 1.65 µm Sa=1.18 to 1.326 µm) are milled with a highest roughness compared to the softest (3M Lava Ultimate Ra= 0.61 to 0.97 µm, Sa= 0.505 to 0.8 µm and Vita Enamic Ra= 0.719 to 0.73 µm, Sa=0.609 to 0.687 µm). Since the 60° inclination is intermediate, there is no clear trend.

A much smaller amplitude of the standard deviations during the 0° inclination angle machining (Ra SD 0.21 to 0.43 µm, Sa SD 0.18 to 0.326 µm), compared to that of the standard deviations of the 60° (Ra SD 0.61 to1.67 µm, Sa SD 0.2 to 2.34 µm) and 90° (Ra SD 0.39 to 2.34 µm, Sa SD 0.21 to 0.67 µm), is observed. In the same way, the differences between the parameters Ra and Sa increase when the orientation successively passes from 0° to 60° and then to 90°. The 90° inclination angle machining generates the largest difference between the Ra and Sa parameters (Ra-Sa=0.6 to 2.93 µm), while the 0° inclination angle machining has almost no difference between the two parameters (Ra-Sa=0.03 to 0.33 µm), regardless of the tool. It is therefore important to use the appropriate inclination angle to obtain the desired roughness when machining dental prosthesis.

The experimental results show, for the 3 inclinations, that there is a predominant influence of the tool on the roughness measured. The roughness for the 60° and 90° inclinations are affected by the diamond grains size of the abrasive mills. While the influence of the diamond grains size on the roughness seems to be non-existent with a 0° inclination angle machining.

### 3.2 Performance Indicators

Performance indicators are used to quantitatively assess the SI and compare it to clinically desired one. A literature study makes possible to establish a preliminary version of the expected clinical roughness specifications on the extrados shape. First, the six roughness parameters (Ra, Rt, Rz, Sa, Sq, Sz) are associated with one or more clinical functions and are quantified with respective indicator of roughness and weight values (Tab. 1).

| Extrados | | | |
|---|---|---|---|
| **Roughness parameter** | **Expected roughness indicator** | **Weight** | **Associate clinical functions** |
| Ra | 0.2 µm | 0.3 | Bacterial plaque retention, wear |
| Rt | 15 µm | 0.1 | Lifetime |

| | | | |
|---|---|---|---|
| Rz | 15 µm | 0.15 | Lifetime |
| Sa | 1.4 µm | 0.1 | Wear, bacterial plaque retention |
| Sq | 1 µm | 0.2 | Optical |
| Sz | 20 µm | 0.15 | Lifetime |

**Table 1**: Expected roughness clinical specifications for the extrados shape.

Then, prediction of roughness before CAD/CAM machining is made possible by the capitalization of previous machining test results. The figure 2 shows roughness parameters prediction overall the crown shape obtained under specifics milling parameters (VITA Enamic biomaterial and lyra bur at a milling feed rate of F2000 mm/min.). Finally, the figures 3 and 4 illustrate the 2 performance parameters results overall the extrados crown shape obtained under specifics milling parameters and according to previous expected clinical functions.

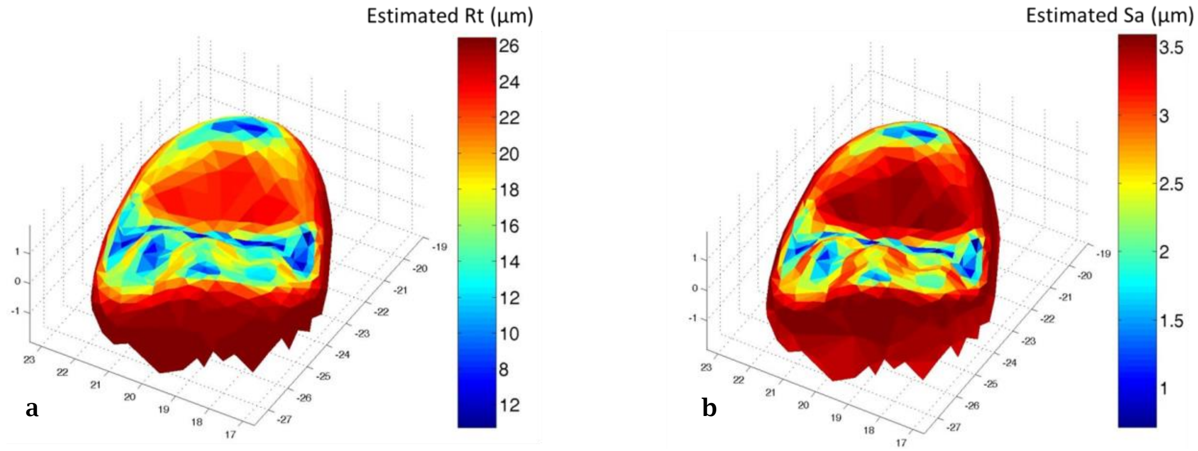


**Figure 2**: Predicted roughness maps with VITA Enamic biomaterial and lyra bur at a milling feed rate of F2000 mm/min. (a) Rt 2D roughness predicted map. (b) Sa 3D roughness predicted map.

Our first case study (Fig. 3) includes 2D and 3D roughness expected clinical functions. The 2 performance indicators ranges are different. The MSI performance indicator ranges from 0 to 8 and the SISD performance indicator ranges from 0 to 11. However, the areas on which the MSI performance indicator is low also correspond to the areas where the SISD performance indicator is low, and conversely. The lowest performance indicators are found on the occlusal face and the highest values on the peripheral faces. On the occlusal areas, the 2 performance indicators low values show that the roughness parameters are close to those clinically expected. From a clinical point of view, functions required in this area are almost respected. On the contrary, on the peripheral areas, the 2 performance indicators high values show that the roughness parameters are far from those clinically expected. The peripheral areas are far from the expected clinical functions. The use of the proposed computer-aided tool highlights the prosthetic areas needed a specific grinding post-processing by the practitioner. The comparison of SI performance indicator maps (MSI, SISD) and tool/prosthesis inclination angle maps highlights the fact that the best SI performance indicators (lowest mean and lowest standard deviation) are obtained during end ball milling with the tool tip. Indeed, on the extrados occlusal area, mostly machined with the tool tip, the roughness specifications are almost respected. Therefore, to best fit the clinical expected functions, peripheral areas have to be machined with another milling path or a 0° inclination angle or might by manually post-processed by the practitioner. In this case study, the 2 performance indicators shape correlation is partly due to the expected clinical functions specifications used.

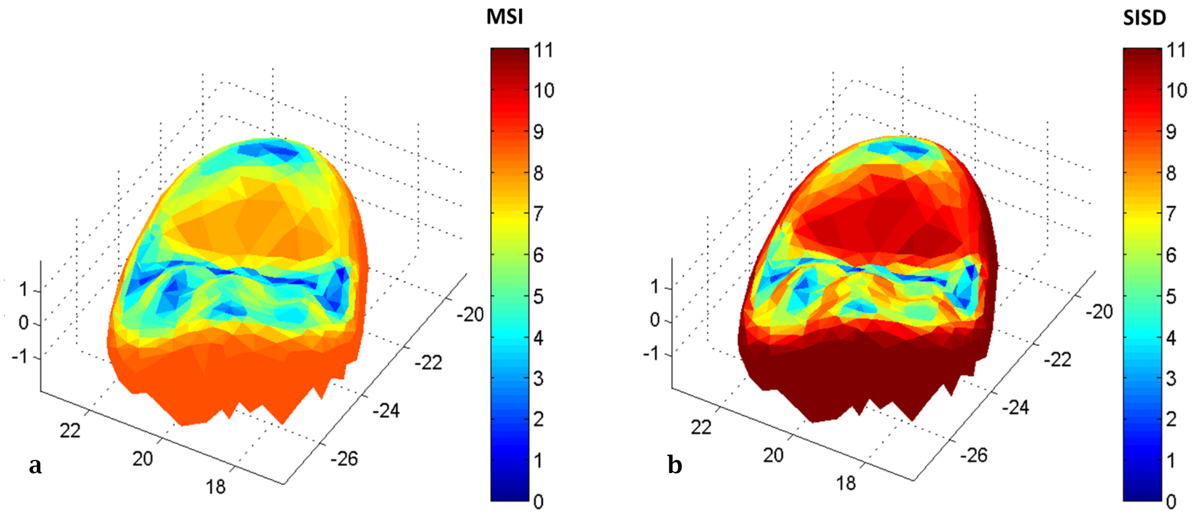


**Figure 3**: Case study 1. Predicted SI performance indicators maps with VITA Enamic biomaterial and lyra bur at a milling feed rate of F2000 mm/min. (a) MSI predicted SI performance indicator map. (b) SISD predicted SI performance indicator map.

Our second case study (Fig. 4) focuses on 3D roughness expected clinical functions. The 2 performance indicators ranges are different. The MSI performance indicator ranges from 0 to 1.5 and the SISD performance indicator ranges from 0 to 0.5. The SISD performance indictor is, all over the shape, lower than the MSI, showing that all the 3D roughness parameters fit all over the shape, with those clinically expected. The comparison of SI performance indicator maps (MSI, SISD) and tool/prosthesis inclination angle maps highlights the fact that best SI performance indicators are obtained all over the crown shape. Nevertheless, during end ball milling, with the tool tip, the performance indicators are the lowest. Indeed, on the extrados occlusal area, mostly machined with the tool tip, the 3D roughness specifications are great respected. In this case, the use of the proposed computer-aided tool highlights that the prosthetic areas don't need a specific grinding post-processing by the practitioner. The second case study performance indicators values are lower than in the first case study, showing that the clinical functions are better complied with. It may be easily to clinically fit with the 3D roughness parameters than with the 2D and 3D roughness parameters.

Both examples lead to conclude that end ball milling is able to manufacture roughness according to those clinically expected. The 2 proposed performance indicators are able to quantify any SI component, or a combination of some well-chosen SI component. In a general case, dealing with another SI component or with others clinical functions specifications, the MSI and SISD correlation might not be the same.

### 3.3 Validation of the computer-aided tool

Aiming to compare the roughness results obtained with the predictive tool to experimental results, 2 crows were machined, and their roughness measured. The crown geometry corresponds to the 2 previous case studies. The selected tool/biomaterial couple was a Lyra bur and an Enamic biomaterial block milled at a programmed feed rate of F2000 mm/min.

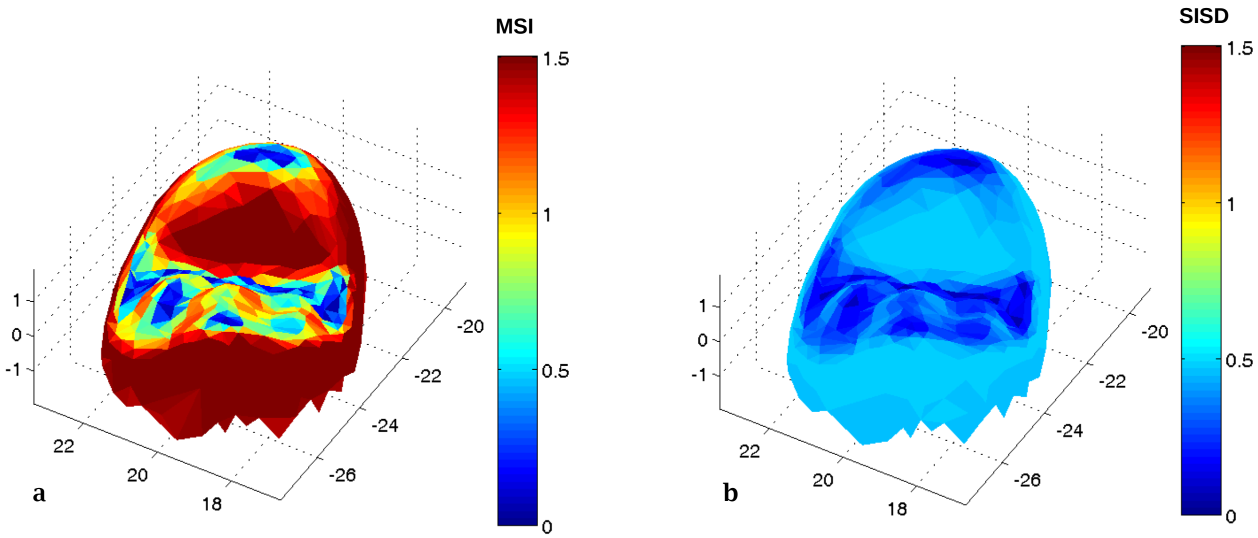


**Figure 4**: Case study 2. Predicted SI performance indicators maps with VITA Enamic biomaterial and lyra bur at a milling feed rate of F2000 mm/min. (a) MSI predicted SI performance indicator map. (b) SISD predicted SI performance indicator map.

The previous 4-axes dental milling center (Lyra prototype; GACD SASU) was used to perform the validation tests. The milling center is fitted with a spindle speed of 60 000 RPM. The machine is warmed up before milling. Coolant is sprayed on the tool-material contact zone. A new bur was used for each crown. Afterward, the roughness was evaluated. The roughness measurement protocol used was that described in section 2.3. To be as close as possible to a planar surface (similarly to section 2.2), the measured surfaces were selected on areas of low curvature. This selection limits the subsequent problems related to roughness measurement on complex shapes. As a result, 3 locations were selected: one on a cusp (point n°1 on figure 5), two others on the peripheral sides (points n°2 and 3 on figure 5). The locations are selected to correspond to areas where the estimated roughness indicators are extreme. Aberrant points from measurements were excluded from the results. For each roughness indicator, an average and a standard deviation of the measurements are calculated.

On the one hand, it is observed, for the 6 roughness parameters, similar indicators on the 2 measured peripheral sides (milled with a 90° inclination angle). On the other hand, the cusp face (milled with a 0° inclination angle) shows lower roughness indicators than those observed on the peripheral sides (milling with a 90° inclination angle). The standard deviations of roughness indicators related to the cusp are lower than those obtained on the peripheral sides. Standard deviations measured in this section on real crowns and those obtained in section 3.1 are similar. The 6 measured indicators are then compared to those previously estimated by the computer-aided tool. The deviations between the measured and predicted roughness indicators are calculated. About the cusp side, larger deviations are observed for the 3D roughness parameters compared to the 2D roughness parameters. The difference for Ra is 0.055 µm (5.7%) and 0.15 µm (15.8%) for Sa. The other roughness parameters give more weight to the extreme values. Their roughness indicator deviations are higher. Except for Sz, the differences remain less than or equal to one micron, which remains acceptable relatively to the manufacturing and measurement dispersions. About the peripheral sides, it is observed larger deviations on the 2D roughness parameters compared to the 3D roughness parameters. The anisotropic topology of the peripheral sides seems to be responsible for this difference. The largest deviation on Ra is 1.126 μm (21.6%) and 0.307 μm (8.8%) on Sa. The highest difference (38.2%) is obtained for Rz more sensitive to extreme points. The measured indicators are slightly lower than those estimated, especially for the 2D parameters. To sum up, there is consistency between the measured and the estimated roughness indicators. Regarding the cusp, the arithmetic roughness indicators measured are quite close, and a larger gap exists for the parameters based on extremums. Concerning the peripheral sides, the predicted values are a bit overvalued for the 2D parameters.

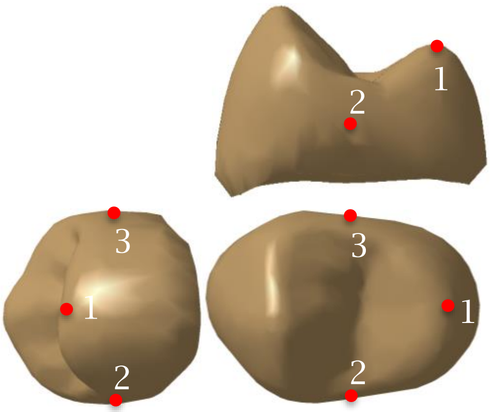


**Figure 5**: Validation roughness measurement localizations.

## 4 CONCLUSION

A computer-aided predictive tool for crown prosthesis SI assessment after milling is proposed. This predictive tool aims at helping the prosthesis manufacturers to choose efficiently milling parameters according to the prosthesis requirements. This modular tool can be enriched by new milling experimental results and new surface integrity components. By the way, 2 SI indicators are being implemented. These indicators are being extended to the relevant SI components correlated with aesthetics, biological response and mechanical behavior requirements for fixed dental prosthesis.

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