There is currently a strong need for fixed prosthodontic restorations in the practice of dentistry.\textsuperscript{1,2} To ensure proper tooth preparation in the anterior sector, where esthetic requirements are crucial, some basic considerations must be kept in mind.\textsuperscript{3,4} Periodontal structures must be respected and tooth preparation must provide a sufficient space to establish a strong and satisfactory esthetic restoration.

To create an esthetic and harmonious appearance between the restoration and adjacent soft tissue, an indiscernible margin for the restoration is typically achieved by placing the finish line (and thus the restoration margin) within the gingival sulcus.\textsuperscript{5} Subgingival finish line preparation, or sulcus penetration, is achieved by using a cutting bur to gradually bury the finish line into an intracrevicular position without violating the biologic width. A major disadvantage inherent to this procedure is the high cutting speed required within the narrow gingival sulcus, which increases the risk of injuring the internal part of the marginal gingiva and periodontal connective tissue attachment.
Consequently, prior to preparation, gingival displacement with a retraction cord is often practiced.\textsuperscript{4,6,7}

Ultrasonic instrumentation has been introduced\textsuperscript{8–10} and successfully applied in periodontology,\textsuperscript{11,12} endodontics,\textsuperscript{13} restorative and prosthetic dentistry,\textsuperscript{14–16} and, more recently, implant dentistry and oral surgery.\textsuperscript{17} Ultrasonic tips have demonstrated two essential qualities: good tactile sense, which allows the operator to perfectly control operative performance, and respect of peripheral soft tissue integrity.

The objective of this study was to develop ultrasonic diamond-coated tips (UDTs) with a deep chamfer profile for intracrevicular finish line preparation and polishing. A new approach that uses these tips during sulcus preparation is proposed for full crown preparation.

**Method and materials**

Prior to the creation of UDTs, the following criteria were established.

- UDTs must have a deep chamfer profile.
- They must be used in conjunction with a piezoelectric handpiece connected to a generator performing at the vibration frequency, amplitude, and power range that have already been proven clinically acceptable when used in contact with soft tissue in periodontics.
- UDTs must demonstrate a sufficient dentin cutting efficiency.
- UDTs must generate a dentin surface roughness close to that generated by a fine grit or red diamond bur of 30-µm diamond grit size (used as a reference).
- They must have an ergonomic shape with a water spray outlet.

**UDT development stages**

Experimental UDTs were developed in two stages. During the feasibility stage, experimental UDTs of different shank shapes and coated with two different sizes of diamond grit (126 µm and 46 µm) were developed to verify that, when used, they could vibrate and cut dentin. During the optimization stage, factors such as a suitable ergonomic shape (shorter and less bent or curved), distance of diamond deposit, and diamond thickness on the tips were perfected, and the final tips were fabricated for further study. Diamond grit sizes on these UDTs were 76 µm and 46 µm. An ultrasonic smooth tip was also developed and tested at this stage.

**Table 1** Summary of tests and analyses

<table>
<thead>
<tr>
<th>Developmental stages/group</th>
<th>Diamond grit size (µm)</th>
<th>No. of teeth</th>
<th>Cutting efficiency*</th>
<th>SEM</th>
<th>Profilometry*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green diamond bur</td>
<td>100</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Green followed by red</td>
<td>100 then 30</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Feasibility phase</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine</td>
<td>126</td>
<td>8</td>
<td>8</td>
<td>8 (16)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>8</td>
<td>8</td>
<td>8 (16)</td>
<td></td>
</tr>
<tr>
<td>Manual (three operators)</td>
<td>126</td>
<td>68</td>
<td>68 (117)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>23</td>
<td>23 (40)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Optimization phase</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manual (one operator)</td>
<td>76</td>
<td>5</td>
<td>5</td>
<td>5 (10)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>10</td>
<td>10 (23)</td>
<td>10 (20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>76 then 46</td>
<td>5</td>
<td>5</td>
<td>5 (10)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>76 followed by 46; then smooth</td>
<td>5</td>
<td>5</td>
<td>5 (10)</td>
<td>2</td>
</tr>
</tbody>
</table>

*Numbers in parentheses = no. of surfaces measured.
Cutting efficiency test and measurement

One hundred forty-two freshly extracted human premolars or molars with no decay were collected and preserved in a hypochlorite solution for use in the present tests and analyses, which are summarized in Table 1. During the feasibility stage, two preparation modes (manually or machine-driven) were assigned at random to each tooth. Machine-driven preparation was performed with UDTs attached to a handpiece fixed to an apparatus developed for this purpose to control speed, direction of movement, and load application. Manual preparation was performed by three different operators. During the optimization stage, the cutting test was performed only manually and by one operator.

Specimen preparation

Each tooth was subjected to coronal preparation in two phases (Fig 1).

1. A gross reduction with a green diamond bur (diamond grit size of 100 µm, #6881-31-014C, Brasseler) mounted on a turbine was performed to place an initial finish line at 1 mm above the cementoenamel junction (Fig 1, left).

2. The final finish line was defined by using the UDTs placed at the initial finish line and parallel to the tooth axis and then simultaneously moved in an apical and horizontal direction (Fig 1, right). The UDTs were mounted on a piezoelectric handpiece connected to a generator (Suprasson P Max, Satelec-Acteon group).

All experiments were performed using the same piezoelectric handpiece and the same power generator. Cutting efficiency was studied when the generator was set at S10 (scaling mode and maximum power at 10) and determined by the amount of tissue removed or the difference in the distance between the initial and final finish lines. Cutting duration was limited to 3 to 4 minutes. During the feasibility stage, the cutting efficiency of the 126-µm and 46-µm UDTs was compared, and during the optimization stage, the cutting efficiency of the 76-µm and 46-µm UDTs was compared.
Surface roughness analysis

The area of interest is the gingival margin floor of the final finish line. Dentin surface roughness was quantitatively analyzed and automatically calculated with an optical profilometer (WYKO NT1100, Veeco Instruments). A scanning electron microscope (SEM) was used to qualitatively analyze the surface status.

Ten teeth were used as controls. Five were prepared with a green diamond bur (#6881-31-014C, Brasseler) and the other five were prepared with the green diamond bur followed by a red diamond bur (#6881-31-014FC, Brasseler).

During the feasibility stage, two manually prepared specimens from the 126-µm UDT group and two from the 46-µm UDT group were selected for SEM analysis. During the optimization stage, two teeth prepared with the 76-µm UDT, two prepared with the 76-µm and then the 46-µm UDTs, and two prepared with the 76-µm UDT then the 46-µm UDT followed by a smooth tip were analyzed by SEM. Five to ten teeth from each group were analyzed with a profilometer. A detailed distribution of the teeth is presented in Table 1. The effect of variations in power setting (S10, S1, or E1) was also examined.

Results

Cutting efficiency

During the feasibility stage, cutting with UDTs of different diamond grit sizes and different shank designs attached to the fixed apparatus did not provide any interpretable results, since tip vibration was blocked or interrupted during tip translation. This blockage was obvious as the load on the tip increased. The results were also variable when cutting was performed by different operators using the same tip. Statistical comparisons of cutting efficiency among the three operators and of machine-driven versus manual cutting were therefore not possible because of these confounding factors during the cutting procedure.

During the feasibility stage, the cutting efficiency of the 126-µm and 46-µm UDTs was equivalent. Within 3 to 4 minutes, an average of 0.5 to 1 mm of tooth tissue was removed, depending on the operator. During the optimization stage and when performed by one operator, the developed 76-µm UDT showed better cutting efficiency (on average, 0.5 mm more of cutting distance) than the 46-µm UDT (Fig 2).

Surface roughness

SEM observation

The SEM images of the finish lines prepared first with a green diamond alone and by a green diamond followed by a red diamond bur are shown in Figs 3a and 3b, respectively. SEM images of the dentin gingival floor prepared with
the 126-µm and 46-µm UDTs with the power set at S10 are shown in Figs 3c and 3d, respectively. At a higher magnification, the dentin surface prepared with a green diamond bur presented concentric indentations, mimicking the rotary mode of functioning of diamond burs (Fig 3e), whereas the UDTs produced linear indentations parallel to the horizontal tip movement (Fig 3f). The spacing and depth of indentations created by both cutting instruments was proportional to the coated diamond grit diameter. The 46-µm UDT visually presented a smoother surface status than the 126-µm UDT (Figs 3c and 3d).
During the optimization stage, by using different developed UDTs, varying the power setting, or by doing both, surface roughness was improved by either using the 46-µm tip and reducing the power setting to S1 or E1 (Fig 4) or by using the smooth tip to polish following the 76-µm or 46-µm UDTs and setting the power at S1 and E10 (Fig 5).

Optical profilometry analysis
The average values for surface roughness (Ra) of dentin prepared with green and red diamond burs and with the 76-µm UDT followed by the 46-µm UDT with the power setting at S10 are summarized in Table 2. The Ra values of the specimens prepared with both the 76-µm and the 46-µm UDTs were superior to those seen for both diamond burs (4.97 and 4.68 versus 4.10 and 2.00, respectively). However, this surface roughness was improved with the UDTs when the power was reduced to S1 or E1 (Table 3) and was better than the value obtained with the green diamond bur. Moreover, when the smooth tip was used following the 76-µm or 46-µm UDT, the resultant average Ra (2.40 and 2.28 with the power set at S1 and E10, respectively) approached the value produced by the control red diamond (2.00). A statistical analysis was not conducted between the results obtained from UDTs and burs because of the high variation in the results obtained from the UDTs and the confounding factors affecting cutting efficiency mentioned earlier.
Discussion

The factors that affect vibration (and thus cutting efficiency) of UDTs have already been determined in root-end ultrasonic preparation as power, tip length, tip orientation, and load applied during instrumentation.\(^\text{18,19}\) The result of the present study shows that when UDTs were attached to a fixed apparatus with a constant load, the vibration was blocked. When different operators used the same ultrasonic diamond tips and generator, variable results were obtained, demonstrating that factors inherent to individual practice habits can influence the vibration (thus cutting efficiency), eg, the pressure exerted on the tips, tip orientation with regard to the tooth surface, and tip translation speed. The most efficient cutting was observed when the operator exerted optimal pressure on the tip with an appropriate tip orientation while slowly translating the tip. This approach, along with the good tactile sense provided by the tips, resembles the action of brushing or sculpting.

The authors noted during the feasibility stage that the 126-µm and 46-µm UDTs did not demonstrate a significant difference in cutting efficiency, despite the presumed superior abrasive capacity of the 126-µm UDT. This may be explained by several factors, such as the distribution and thickness of diamond deposition affecting the tip’s vibration. However, when the tip shape was modified to be more curved in the optimization stage, these factors did not seem to affect the vibration potential. The developed 76-µm UDT with larger grit diameter thus showed a higher cutting efficiency than the 46-µm UDT.
The present study demonstrated that the surface generated by UDTs (indentations parallel to the horizontal tip translation) was different than that generated by diamond burs (concentric indentations corresponding to the rotary movement). The present results also partially confirm the finding of Laufer and coworkers\(^\text{16}\) that UDTs generated a rougher surface than diamond burs. A reproducible, precise, and smoother surface at the finish line plays a significant role in a prosthetic construction leading to the least gap space formation.\(^\text{20–24}\)

The present study showed that it was possible to improve the surface roughness in two ways: either through the use of a 46-µm UDT with a reduced power setting (E1 or S1) or through the use of a smooth tip to polish the finish line, along with a power setting of S1 or E10.

In spite of their direct contact with soft tissues, UDTs are atraumatic to periodontal tissue, as clinically observed when they are used for root planing in periodontal pockets. The percussion mode of ultrasonic vibration at an appropriate amplitude results in no tearing of the soft tissue. With the same amplitude and frequency used in periodontics, the UDTs developed here for sulcus penetration also carry this advantage. Gingival protection via the use of a retraction cord thus becomes unnecessary.

The final UDTs presented efficient dentin cutting capacity, as the finish line could be placed into an intracrevicular position for a distance of 0.5 to 1 mm within 3 to 4 minutes. The working time needed to perform this sulcus penetration is longer than when a green diamond bur is used. However, this time should be clinically acceptable as it is unnecessary to pack a cord into the gingival sulcus.

**Proposal for a new intracrevicular preparation protocol**

After obtaining the final results from the optimization stage of UDT development, the authors fabricated prototypes consisting of 76-µm and 46-µm UDTs and a smooth tip (Fig 6). These UDTs were then registered and certified by the G-MED agency (a quality certification body in the medical and health field) to be used with safety in clinics with a Conformité Européene marking.

**Clinical illustration of protocol**

A number of patients requesting esthetic full crown restorations were selected. Informed consent was obtained prior to the beginning of the procedure. Two phases of preparation are distinguished (see Fig 1): the rotary phase, or supragingival or juxtagingival preparation, and the ultrasonic phase, or sulcus penetration. A summary of proposed tips and power settings is provided in Table 4. Once a gross reduction of tooth structure above the gingival line with a diamond bur mounted to a turbine is completed, ultrasonic sulcus penetration can begin. No gingival retraction with

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Table 4  Summary of recommended tips and power settings for finish line preparation, finishing, and polishing

<table>
<thead>
<tr>
<th>Protocol/sulcus penetration step</th>
<th>Ultrasonic tip</th>
<th>Power setting*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finish line preparation</td>
<td>76 µm</td>
<td>S10</td>
</tr>
<tr>
<td>Finishing</td>
<td>46 µm</td>
<td>S10</td>
</tr>
<tr>
<td>Start polishing</td>
<td>46 µm</td>
<td>E1</td>
</tr>
<tr>
<td>Polishing Simplified</td>
<td>Smooth</td>
<td>S1 or E10</td>
</tr>
<tr>
<td>Finish line preparation and finishing</td>
<td>46 µm</td>
<td>S10</td>
</tr>
<tr>
<td>Polishing</td>
<td>46 µm</td>
<td>S1 or E1</td>
</tr>
</tbody>
</table>

*The power generator for the power indicated in the table is PMax Suprasson (Satelec-Acteon group).
a cord is necessary. Only appropriate and sufficient pressure (i.e., not too high) is needed to cut efficiently without blockage. The operator should perform with a sensation of sculpting rather than cutting the tooth tissue.

The 76-µm UDT is used with the power set at S10 to gradually bury the finish line into the gingival sulcus (Figs 7a and 7b). Water irrigation from the water spray outlet aimed at the active part of the tip provides the operator with a clean and clear operative field. The finish line is then completed with the 46-µm UDT, with the power still set at S10. At this point, any sharp edges created by the chamfer profile of the 76-µm UDT can be eliminated (Fig 7c).

To polish the finish line, first the 46-µm UDT is used with the power set at E1. This is followed by the smooth tip with the power set at S1 or E10 (Fig 7d). The surrounding gingiva is not injured during preparation with the UDTs (Fig 7e). A clean impression with a sharp gingival margin is thus obtained (Fig 7f), and prosthetic treatment can continue.
This protocol can be simplified by employing only the 46-µm UDT (Table 4). Following gross reduction with a diamond bur of appropriate shape, only the 46-µm UDT is used for preparation and finishing steps, with the power set at S10. Then the polishing step is continued with the same tip, with the power set to S1 or E1. This protocol takes slightly longer to achieve the equivalent cutting efficiency.

Conclusions

The developed ultrasonic diamond tips demonstrated efficient dentin cutting. Dentin surface roughness obtained with the smooth tip was comparable to that obtained with the referenced red diamond bur. When used appropriately in the clinical situation and in direct contact with gingival tissue, these ultrasonic tips can precisely place a finish line in the gingival sulcus without injury to the marginal periodontium. The obtained cervical finish line is very clear and clean, with a sharp gingival margin.

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