Automatic Algorithm to Design Bespoke Teeth Whitening Trays

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Abstract. The growing attention of people to aesthetics has led to a greater demand for dental whitening treatments. Several solutions can be utilized to obtain the desired visual whiteness of teeth but, according to literature, at-home supervised treatments are the standard in dental bleaching. They require soft plastic trays to contain a whitening gel, with active chemical agents, and keep it in contact with the patient's teeth. The fitting, comfort, and tightness of trays play a fundamental role in the treatment. Any gel leakage can compromise the effectiveness of the treatment and damage soft tissues. Commonly, the trays are ready-made or based on physical dental impressions and manually modified by the dental technician. These procedures have low repeatability and do not always ensure high accuracy. This work presents an automatic digital algorithm to design customized whitening trays. Starting from a digital scan acquisition of the patient's dental arches, it generates the 3D models of the bespoke trays, in approximately two minutes per arch, ready to be produced by additive manufacturing and thermoforming technologies. The evaluation of the method involved 20 patients. The results emphasize that the custom trays were comfortable and ensured high levels of tightness and fitting.

Keywords: automatic product design, digital process, custom teeth trays, dental whitening
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1 INTRODUCTION

Aesthetic dental treatments have grown notably in importance in the 21st century due to the increased awareness of patients. Nowadays, the color of the teeth can influence a person's self-esteem, satisfaction and interpersonal relationship [11]. The outer part of a tooth is called enamel. It is composed of about

97% of hydroxyapatite which is naturally white and translucent. However, the daily routine and some habits such as smoking and the consumption of tea, wine or coffee can compromise the natural color of the enamel [9]. Furthermore, mechanical abrasion and age play a role in the teeth color. When the enamel becomes thinner due to erosion, the inner part of a tooth, called dentin, becomes more and more visible and the global teeth color become darker [2]. For these reasons, it could be seen an increased demand for bleaching dental treatments in recent years.

Currently, to increase the visual whiteness of teeth there are various systems. They can be classified according to the whitening agent used, its concentration or the method used for the application. Based on the chemical agent, the most common bleaching agent currently used are hydrogen peroxide and carbamide peroxide. Hydrogen peroxide constitutes the active element of the whitening, which reacts directly with the colorful pigments of the teeth. Carbamide peroxide, instead, breakdown in urea and hydrogen peroxide. The resulting effect depends on the hydrogen peroxide concentration plus its application time and method [12].

According to the whitening technique adopted two main types of treatments can be identified: in-office and at-home systems. In-office treatments use gels with a higher concentration of hydrogen peroxide, usually in the range of 30-38% and takes less than an hour [3]. This procedure can only be performed by dentists. Patients can experience an immediate whitening of the teeth but, due to the high percentage of the active agent present in the bleaching product, the results can also be associated with high tooth sensitivity. Moreover, at these concentrations, the agent is harmful to soft tissues. To avoid ulcers, the gum and tongue need to be protected. Usually, water-soaked gauze or rubber dam are used [9]. Sometimes even standard or, in a few cases, custom trays are utilized. In-office systems also have higher costs and chair-time.

At-home treatments aim to limit these side effects. However, the usage of active agents in a domestic environment in Europe is regulated by the EU Council Directive 2011/84/EU which states that: a maximum concentration of 0.1% of hydrogen peroxide present in oral products or released from other compounds or mixtures can be used in oral whitening products. Products containing hydrogen peroxide in the range 0.1 - 6% can be used only after clinical examination and cannot be directly available to the consumers [7]. This regulation subdivides at-home products into two different categories according to the chemical agent concentration, respectively the over-the-counter (OTC) and at-home supervised system. The OTC group comprises all the products that can be acquired directly in drugstores or supermarkets by the patients without the supervision of a dentist. They include whitening strips, toothpaste and whitening rinses. However, these solutions have a lower bleaching potential compared to the previous methods due to the lower concentration of hydrogen peroxide (less than 0.1%) or the usage of alternative chemical agents like sodium chlorite [3].

The supervised at-home treatments consist of soft plastic trays, that can be of fixed size or modeled on the patient's teeth. They are used to contain the whitening gel and keep it in contact with the teeth. Generally, the application is overnight for two to six weeks with a gel containing from 10 to 16% of carbamide peroxide. This method requires the patients' commitment for optimal results. The dentist should instruct them on how to place the gel into the trays [14]. Evidence suggests that the whitening effect of at-home treatment with 10% of carbamide peroxide for 14 nights compared with two in-office weekly sessions of 30 minutes with a gel containing 35% of hydrogen peroxide is more than doubled. Moreover, according to literature, the chair-time, costs and side-effects are reduced and it is considered the standard in teeth whitening [3].

The design of bespoke trays that fit the patients' teeth plays a fundamental role in the prevention of the possible side effects of the at-home supervised or in-office treatments mentioned above, as well as guaranteeing and improving the effectiveness of the tooth whitening. Currently the ready-made mouth trays available on the market are filled with silicone. The patients can create the impressions by biting the insert and then insert the gel in them. More conventional solutions used by dentists consist of dental trays filled with deformable materials [5] to obtain the patient's impression. This is used as a mold to obtain the teeth plaster model. On the model the dental technician can create an offset, to contain the whitening product, by depositing manually some material (e.g. wax or liquid photoresin). Then this modified model is used to thermoform the custom tray for the patient [6]. The thermoformed tray is manually cut along the margin line between

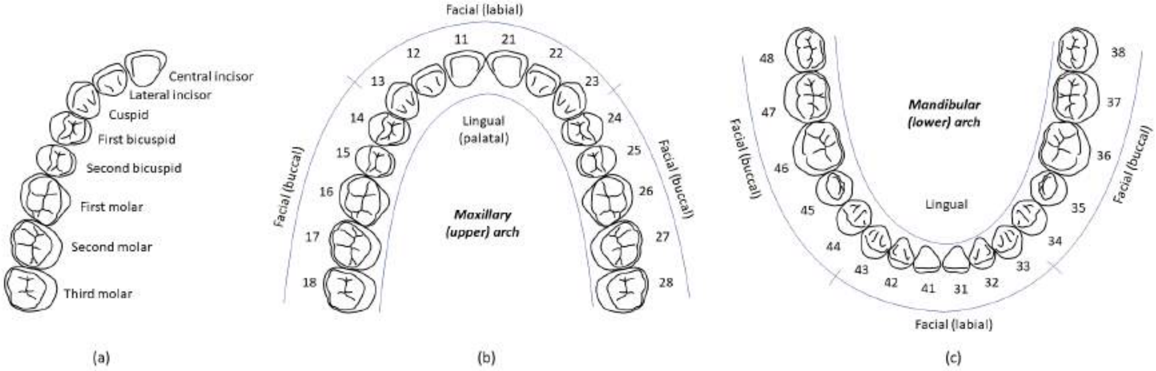

Figure 1: Teeth (a) and oral cavity designation for upper (b) and lower (c) arch using traditional and two-digit nomenclature based on the standard ISO 3950:2016.

teeth and gingiva to reach its final shape. The use of impressions does not always guarantee high dimensional accuracy due to possible failures like a limited surface of teeth captured, inadequate amount of details or distorted shapes [4]. Furthermore, this manual procedure strongly depends on the experience and dexterity of the dental technician and therefore has limited repeatability.

The following sections present a novel algorithm that allows us to automatically generate bespoke trays models optimized for comfort, fitting and tightness. The trays have been evaluated through 20 supervised at-home treatments starting from the digital acquisition of the patients' teeth to the final custom trays used for the whitening.

2 METHODS

This automatic procedure to obtain a bespoke tray for dental whitening is based on the oral cavity designation illustrated in Figure 1. In particular, teeth traditional names like incisors or molars (a) can also be substituted by the two-digit classification defined in the standard ISO 3950:2016 [10] for the maxillary (b) and mandibular (c) arches. The inner part of the oral cavity is called lingual, while the whole outer part is called facial.

The automatic digital procedure requires as starting point an accurate digital representation of the patient's teeth. Intraoral scanners are suitable for this. They capture optical impressions by projecting a light source onto the dental arches. The output consists of point clouds that are processed and triangulated, usually by the same 3D scanning software, to create a 3D surface mesh [13]. Once the shape of the two arches have been acquired, they can be individually processed to produce the trays. In current dental practices, unless there are particular discolorations, dentists usually whiten teeth up to the second bicuspid [6]. For this reason, the final resulting trays should fit the teeth till the seconds molar (_7th) and should have an offset on the facial surface and partially on the lingual surface of the teeth till the second bicuspid (_5th).

2.1 Automatic Algorithm

Figure 2 illustrates a schematic representation of the automatic algorithm' steps. The input consists of the 3D surface obtained with the intraoral scanner, which is typically an STL or PLY file. An example of maxillary arch is visible in Figure 3(a). Usually, these models are very detailed, with more than 100k triangles. The first step consists in reorienting the model. Its principal directions are aligned with the XYZ axis. The XZ plane is the occlusal plane, while the Y axis points in occlusal direction, as can be seen in the upper arch in Figure

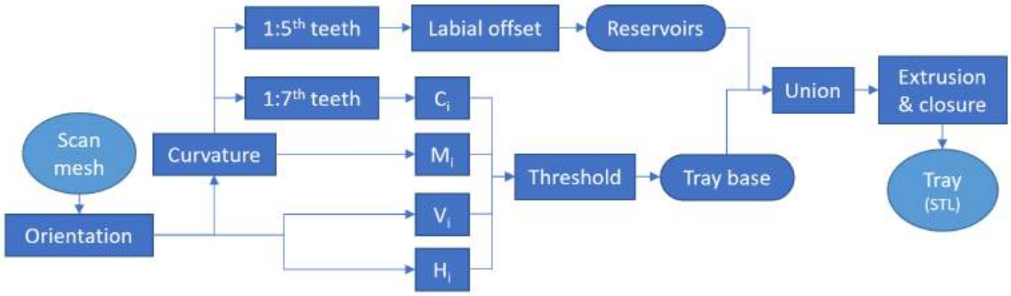

Figure 2: Schematic diagram of the automatic algorithm

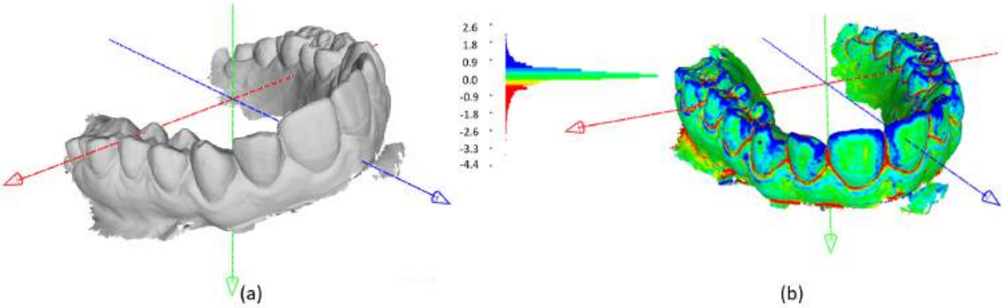

Figure 3: The initial model of the teeth obtained by intraoral 3D scanning (a) and the mesh after the reorientation and computation of local curvature (b). Vertices in red have negative curvature values.

3(b).

On this surface, the principal directions of the curvature is computed using the pseudoinverse quadratic fitting method. In Figure 3(b), the color mapping displays the mean curvature values of the vertices. Negative values (in red) represent concave areas. They are used to cut the model and obtain a preliminary separation between teeth and gum. In the literature there are many solutions for tooth segmentation including deep-learning-based and geometric methods [8, 17]. This work analyzes multiple geometric features of the model and combines them to obtain the final whitening tray with reservoirs.

In parallel with the curvature analysis, four other qualities (V_i, H_i, M_i, C_i) are computed on each vertex of the reoriented mesh to distinguish teeth from gum. Each vertex of the mesh assumes a float value from 0 to 1 for each quality. The value 0 corresponds to definite gum while 1 identifies the teeth (Figure 4).

V_i maps the vertical position of each vertex and normalizes it based on the dimension of the mesh bounding box on the Y axis (a). The preliminary reorientation of the model is fundamental for this quality, and it is differentiated between maxillary and mandibular arches. Considering that the Y axis always points towards the palate, for mandibular arches, the higher is the vertex position, the greater is the probability that the vertex belongs to a tooth. It is the opposite for maxillary arches.

H_i considers the euclidean distance of the vertices to the mesh center in the XZ plane. This value is normalized by the bounding box size along the X and Z axis (b).

To evaluate M_i, the algorithm looks for the local maxima of the mesh. The quality represents the geodesic

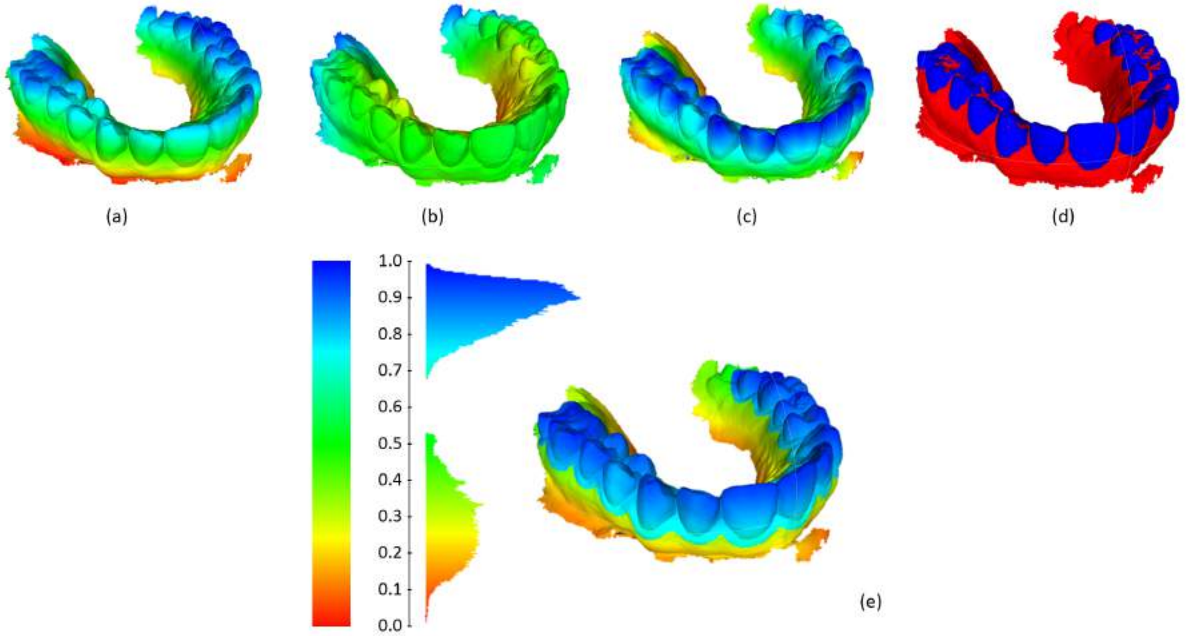

Figure 4: The four parameters used for teeth/gum segmentation, each displayed with an RGB scale where blue (1) is teeth, red (0) is gum. V considers the vertical coordinates (a), H evaluates the XZ planar coordinates (b), in M the local maxima of the mesh are computed (c), and C exploits the curvature cut and the following elaboration of the mesh (d). The combination of the four components gives (e).

distance between each vertex and the selected points. Lower is this value, greater is the probability to identify a tooth cuspid. The last quality takes advantage of the previous curvature computation. Usually, vertices on the teeth-gum border have negative curvature. This allows us to separate the mesh into the two main categories. Figure 4(d) illustrates this binary separation between teeth and gum. In this step, possible third molars are also neglected and their vertices are classified with 0, because the tray should cover only teeth till the second molars. For each vertex, each quality is multiplied by a constant factor (empirically determined), and the sum is computed. Analyzing the normalized quality histogram of this new model (Figure 4(e)), it is visible a clear distinction between teeth and gum on the graph. Selecting the teeth area and expanding the boundary to include a small part of gum, the algorithm delete the remaining faces and outputs the initial tray. To avoid jagged edges on the final mesh, it is performed a Laplacian smoothing on the border. An example is visible in Figure 5(a).

The following step consists of the selection and creation of the reservoirs to contain the whitening gel and protect soft tissues. These reservoirs, in the algorithm, cover the facial side of teeth till the seconds bicuspid plus about half lingual side of the same teeth. The size of the offset from the mesh obtained in the previous step for the reservoir is 0.2mm. This value is the result of preliminary tests carried out on several trays to verify if it could be suitable for its purposes.

The scalar product between each vertex position and the surface normal vector on that point is computed to find the area of the mesh to thicken. Considering that the origin of the coordinate system coincides with the barycenter of the mesh, facial vertices mainly result with a positive scalar product. Processing these outcomes, it is possible to identify and then thicken the desired area, as shown in Figure 5(b). The model of the tray is

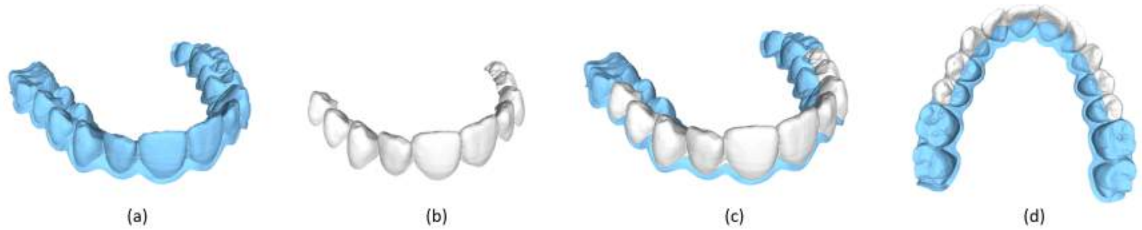

Figure 5: After the computation of the tray without reservoir (a) and the offset of 0.2mm for the gel on the teeth till the seconds bicuspid (b) a Boolean union is computed (c, d) to obtain a unique mesh with reservoirs.

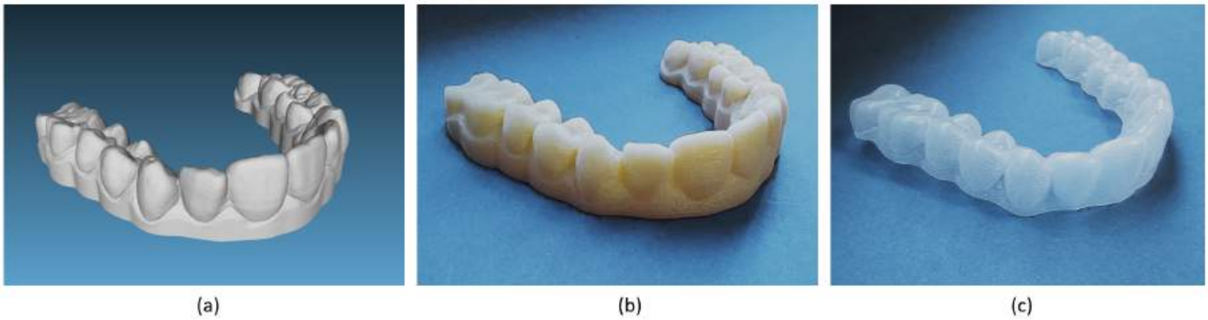

Figure 6: The final digital model of the tray (a) and the output from the additive manufacturing (b) and thermoforming (c) procedure.

obtained through a Boolean union between models (a) and (b). Figure 5(c) shows the two models overlapped, while (d) is the unique mesh obtained after the union.

The automatic algorithm has been fully implemented using the Python language. It is worth nothing that it can be used fully automatically, but also with a manual intervention. To take into account the high variability of the oral cavities among patients, the user has also the possibility to modify some parameters by a simple graphical user interface. For example, some of the adjustable parameters are the value of the curvature thresholds for segmentation, the multiplicative constants of the 4 qualities to alter their importance. For this reason the procedure has been ideally split into its six main steps: orientation, teeth segmentation, initial tray creation, reservoirs creation, models' union, final output ready for the production. At the end of each step, a preview of the partial 3D models of the main steps of the elaboration procedure is visible. This helps the users to adjust the parameters to improve the quality of the tray, allowing them to observe how the output is modified according to the new input values.

Although the global shape of the tray with reservoirs is fully defined after the union operation, the additive manufacturing process for production requires a last step. The border of the model must be extruded downward and closed with a plane as illustrated in Figure 6(a). The final output is an STL file ready for the production. Figures 6(b) and (c) illustrate respectively the 3D printed reference model of the arch and the actual whitening tray thermoformed and cut out.

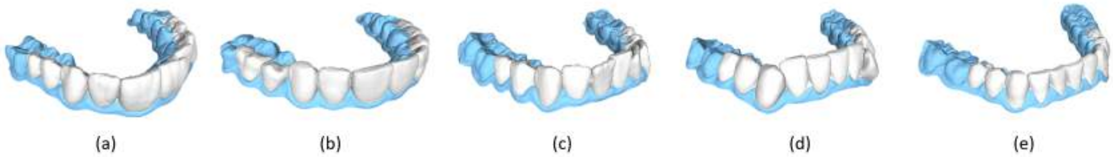

Figure 7: Some output files of trays with reservoirs used for the validation. The subset includes both maxillary (a, b) and mandibular (c, d, e) arches.

2.2 Case Study and Validation

To evaluate the proposed algorithm, a validation protocol has been defined with the support of a dentist. 20 patients aged between 18 and 60 years (11 male and 9 female) have been recruited to perform an at-home supervised whitening treatment. Informed consent was obtained by all patients. A flyer including a description of the whitening treatment, how it works and possible side effects was given to all patients.

After a preliminary visit to exclude any possible contraindication, the dentist acquired digital 3D scans of each patient's oral cavity by using the 3Shape Trios3-basic intraoral scanner [1]. All acquired data have been anonymized prior the elaboration through a coded classification.

The input data was processed using the automatic algorithm to obtain the final STL files of the upper and lower trays with reservoirs. The whitening trays were produced with an additive manufacturing process and subsequent thermoforming. The 3D printer used was a Stratasys J700, which uses a material jetting technology and the VeroDent^{TM} (MED670^{TM}) peach-tone photoresin [16]. Material jetting printers work similarly to traditional two-dimensional inkjet printers. The printhead dispenses droplets of a liquid photosensitive resin onto the build plate that solidifies under a UV light fixed behind the printhead. Once the layer is completed, the build plate is lowered and the deposition is repeated layer by layer to realize the 3D component. The result of this process consists of high quality reference models made of dental materials.

Subsequently the trays are produced with a thermoforming process of a plastic material disc on the 3D printed reference models. The thermoforming machine used is a Scheu-Dental Ministar S®. It operates with 1mm polyethylen low density discs, named Copyplast®[15]. Finally, the trays are obtained by trimming the deformed disc along the smoothed border as showed by the STL file obtained by the algorithm.

The whitening trays were shipped to the dentist, who instructed the patients on how to use them. Each patient received the pair of trays made for them, and a set of commercial whitening gel syringes (Opalescence PF 10% of carbamide peroxide). The whitening treatment lasted fortnight. The patients were asked to fill the reservoirs of each tray with $1/4$ of gel in the syringe (0.3 ml of gel) and wear the trays at night, for 7-9 hours.

3 RESULTS

During the supervised at-home whitening treatment all 20 patients compiled an anonymous daily report about the comfort, fitting and tightness of the bespoke trays, plus they should indicate the number of hours spent wearing the tray in the nighttime. After 14 nights, they filled in a questionnaire about the general experience and the level of satisfaction. Finally, the dentist performed a further control visit to verify the whitening progress of the treatment.

From the daily reports it emerges that patients respected the medical indication, and wore the trays for about 8 hours per night (mean: 8.0h, SD: 0.7h). Fifteen patients did not report any gel leakage during the whole treatment. None of them reported leakage during the nights. Two patients reported gel leakage during the first two attempts of wearing the trays, while three only for the first one. None of them stated it anymore during the rest of the treatment.

No patients reported issues about fitting problems or discomfort caused by the trays. Only two persons reported small difficulties in wearing the trays the first time, but none of them highlighted any trouble from the second night till the end of the treatment.

The analysis of the questionnaires shows that the global level of satisfaction is medium-high (12 high, 8 medium, 0 low). All the patients would recommend the treatment to others.

According to the dentist, the trays are effective for whitening treatments from a clinical point of view. The dentist did not report any damage to the soft tissues, thus confirming that the fitting and the offset were able to contain the bleaching gel. To conclude, all patients reported an improvement in the teeth shade. Fifteen patients even reached the maximum value of dental whitening (shade A1 of the VITA classical A1-D4®scale).

4 DISCUSSION

The results of the tests highlight that the design of bespoke trays satisfied the required needs of comfort, fitting and tightness for the whitening treatment. All bespoke trays fitted the patients' dental arches, and the offset ensured the tightness of the gel during the whitening treatment. Based on the dentist's opinion, and also on the basis of the patients' opinions reported in the questionnaires, the gel leakage occurred to few patients and particularly during the first experience in wearing the trays. This may be mainly due to the patients' inexperience in gel deposition. In fact, the quantity of gel could be excessive or its deposition into the trays could be wrong. Importantly is that no patients manifested gel leakage at nighttime or in the following days of the treatment.

An additional major contribution of this work regards the processing time required to create a bespoke pair of trays. Being an automatic process, the elaboration time mainly depends on the computational performances of the personal computer used. In this study, an ordinary notebook computer has been used. The approximate average time required for the fully automatic procedure was about 2 minutes. Only 3 trays out of 40 required a manual modification of the predefined parameters. It was simply done by modifying the values using sliders in graphical user interface of the application. In a few seconds, the program re-computed the results of the modified step. Once accepted by the user, the algorithm continued till the final creation of the STL file.

Compared to the traditional manual procedure to produce whitening trays, the developed algorithm improves also the repeatability of the design. While the first is highly dependant on the operator's dexterity, the second will generate the same tray if the input scans and the set parameters of the algorithm are the same. An additional benefit is that a fully automatic digital procedure like this one can be more easily combined with a production process based on additive manufacturing, and also diminishes the operators' workload.

5 CONCLUSIONS

In recent years, the growing attention of people to wellbeing and aesthetics led to an increment of the demand of aesthetic dental whitening treatments. The natural color of the teeth enamel can be affected by several factors, but techniques to restore the teeth whiteness are today available.

Traditional at-home supervised bleaching treatments usually involve the usage of physical dental impressions used as molds, plaster models and manual modifications to generate the trays that contain the whitening gel. This procedure does not always guarantee high accuracy and it is highly dependant on the dental technician's experience.

This work presents an automatic digital algorithm to design bespoke whitening trays. Starting from a digital scan acquisition of the patient's dental arches, it generates the bespoke models of the trays as STL files in approximately 2 minutes per arch. The output is ready to be produced with additive manufacturing and thermoforming technologies.

The method has been evaluated with 20 patients. Test results highlight that the trays were comfortable and the combination of the bespoke design with the automatic generated offset ensured high levels of fitting and tightness. The whitening gel was kept in place within the trays. No patients manifested gel leakage at night or soft tissue damages. 15 out of 20 patients reached the maximum shade of whiteness.

These results related to aesthetic and comfort combined with the limited computation time required by the algorithm, the higher repeatability of the output, and the digitalization of the procedure can expand the field of application. A possibility could be using the algorithm to design trays for the in-office treatments, that make use of gels with higher percentages of the active whitening agent.

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