DenTiUS Plaque: a web-based application for the quantification of bacterial plaque

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Submitted to: Journal of Medical Internet Research
on: March 25, 2020

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Abstract

Background: In the dentistry field, the analysis of dental plaque is vital because it is the main etiological factor in the two most prevalent oral diseases: caries and periodontitis. In most of the papers published in the dental literature, the quantification of dental plaque is carried out using traditional, non-automated, and time-consuming indices. Therefore, the development of an automated plaque quantification tool would be of great value to clinicians and researchers.

Objective: To develop a web-based tool called DenTiUS and various clinical indices to evaluate dental plaque levels using image analysis techniques.

Methods: The tool is executed as a web-based application to facilitate its use by researchers. Expert users are free to define experiments, including images from either a single patient (to observe an individual plaque growth pattern) or several patients (to perform a group characterization), at a particular moment or over time. A novel approach for detecting visible plaque has been developed as well as a new concept known as non-visible plaque. This new term implies the classification of the remaining dental area into three subregions, according to the risk of accumulating plaque in the near future. New metrics have also been created to describe visible and non-visible plaque levels.

Results: The system generates results tables on the quantitative analysis with absolute averages obtained in each image (indices about visible plaque) and relative measurements (indices about visible and non-visible plaque) relating to the reference moment. The clinical indices that can be calculated are the following: the plaque index of an area per intensity (API index, a value between 0-100); the area growth index (growth rate of plaque per unit of time in hours - percentage area/hour); and the area time index (the time, in days, needed to achieve a plaque area of 100% concerning the initial area at the same moment). Images and graphics can be obtained for a moment from a patient and in addition to a full report presenting all the processing data.
Dentistry experts evaluated the DenTiUS Plaque software through a usability test, giving the best-scoring questions those related to the workflow efficiency, the value of the online help, the attractiveness of the user interface, and the overall satisfaction.

Conclusions: The DenTiUS software allows an automatic, reliable and repeatable quantification of dental plaque levels, providing information about area, intensity and growth pattern. Dentistry experts recognized that DenTiUS Plaque software is suitable for quantification of dental plaque levels. Consequently, its application in the analysis of plaque evolution patterns associated with different oral conditions, as well as to evaluate the effectiveness of various oral hygiene measures, can represent an improvement in the clinical setting and the methodological quality of research studies.

(JMIR Preprints 25/03/2020:18570)
DOI: https://doi.org/10.2196/preprints.18570

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Author's contributions

N Vila-Blanco, V Freire, C Balsa-Castro and MJ Carreira designed and implemented the whole platform; MJ Carreira, C Balsa-Castro and I Tomás supervised the implementation, designed the image processing algorithms and defined the clinical indices.

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Keywords: computer-aided diagnoses; computer-based biomedical applications; dental health; dental plaque quantification; web-based systems

Introduction

Dental plaque is a diverse community of microorganisms, and is located on dental surfaces in the form of a biofilm embedded in an extracellular matrix of polymers from both the host and the microbiota [1, 2]. It is known that plaque is directly related to the appearance and progression of common oral pathologies like caries and periodontal diseases [3, 4]. The monitoring of how it develops is, therefore, a topic of great clinical importance when it comes to establishing better strategies for the control of oral diseases caused by bacterial biofilms [5]. Several clinical indices for quantifying dental plaque have been developed over recent decades. These have been frequently used by the research community and in the clinical setting to evaluate the efficacy of different oral hygiene products. Some of these traditional plaque indices include those developed by: Ramfjord [6]; Greene and Vermillion [7]; Quigley and Hein [8], later modified by Turesky *et al.* [9]; Löe [10]; and O'Leary [11]. In general, most of these conventional indices employed an ordinal scale as part of a simple and semi-quantitative method to evaluate surfaces covered by dental plaque. Their application, however, has major limitations, given the great subjectivity inherent in conducting visual examinations. Furthermore, the visual method is very imprecise when plaque levels are low or particularly high, and such clinical investigations are often laborious [12].
The planimetric method [13] was an improvement and involved taking a photograph of dyed plaque and determining its extent. This approach was much more accurate, as it employed a more objective measure to assess plaque levels (it produced a continuous, rather than ordinal, output). Additionally, as image sensors have improved year-on-year, the quality of the images generated is better than ever. Nevertheless, this is still a time-consuming process because the teeth and plaque regions in each image must be outlined by hand.
It was only in the 21st century that experts began to rely on techniques that employ analyses of digital images to quantify dental plaque. The main approach involved the planimetric method, with an imaging tool used to detect the dental plaque and tooth areas individually and calculate the ratio between them. An expert operator could outline both regions manually using a graphical interface [14, 15]. Also possible were semi-automatic approaches, whereby the image-processing algorithm required intervention from the dental expert to work [16, 17], or images could be segmented automatically using image-processing techniques [18-20].
Some researchers used image-processing software [16, 17, 21-23] or general-purpose data-

processing tools [24, 25], while others developed their own methods to process these images [24, 26]. More recently, specific dental-assessment software has been used to quantify plaque levels [18, 27].

The computer-vision techniques used previously vary from rudimentary to extremely complex. One of the simplest methods was image thresholding, which made it possible to isolate two or more different areas according to their color or light intensities. This technique was able to distinguish between: disclosed plaque and non-plaque [24, 28]; teeth, plaque, and gingiva pixels [23]; and isolated teeth, gums, plaque and background areas [29, 30]. More sophisticated machine-learning algorithms were subsequently developed to enhance the results. Carter *et al.* [20], for example, created a database of more than 600,000 pixels to analyze the relationship between pixel information (in both the RGB and HSI space) and pixel location (disclosed plaque, tooth and gingivae). The information in this large table enabled a further step to be taken to create a classifier capable of labeling a pixel in a new image in its most probable location. Clustering methods have also been employed. An example is the approach adopted by Kang *et al.* [31], who used a combination of Fuzzy C-Means and Cellular Neural Network algorithms to classify image pixels into plaque, tooth surfaces, and backgrounds. A mean-shift based clustering algorithm was also used for plaque segmentation [19].

The different methods available today produce promising results, with many studies reporting the suitability of automatic or semi-automatic techniques for assessing dental plaque and, as a result, oral hygiene levels [16-18, 24, 27, 29, 32]. Specifically, quantitative light-induced fluorescence digital (QLF-D) is an adaptation of QLF which employs a modified filter set (D007; Inspektor Research Systems BV, Amsterdam, The Netherlands), narrow-band violet light (405nm) and a high-specification digital single-lens reflex (SLR) camera. This configuration has been specifically developed to enhance the visualization and quantification of dental plaque [33-35].

Following this trend of digital development, we present DenTiUS Plaque, which is a tool we have developed to enable the automatic assessment of dental-plaque levels. DenTiUS Plaque was first envisaged as a standalone application. However, as we wanted to permit web access for expert users, a more general platform (DenTiUS Lab) was designed to separate the processing stages (DenTiUS Plaque proper module) and enable the execution of administrative tasks like user and patient management. The system also has a common interface where users can log in, include patients in the database, and interact with the DenTiUS Plaque module independently. The entire platform is web-based, and so it can run on every web browser. It also has a friendly operator interface for non-technical users.

The rest of the paper is structured as follows: The Methods section first describes the entire platform, including its main features and software architecture, and also contains a brief description of the patient database; then it explains DenTiUS Plaque, describing the kinds of the image it can process, the experiment's design, and the processing algorithms. In the Results section, the different parameters of the quantitative analysis of dental plaque offered by the tool are presented, as well as several graphics, through a real case; subsequently, the results of a questionnaire to individuals working in the field of dentistry on the usability of software are presented to evaluate the ease of use of the instrument and its usefulness. Finally, the paper closes with a discussion, some closing remarks and identifies possible future improvements.

Methods

DenTiUS structure

The DenTiUS platform emerged naturally as a way to manage users, images, and patients in dentistry research. It was initially developed as a standalone application for the quantification of dental plaque, with modules for managing the patients and experiments of a unique user, but not the different profiles and interactions of multiple users. As our research group is also working in other dentistry fields, all of which employ a shared patient- and user-database, the decision was made to develop an entire web-based system, DenTiUS Lab, for dental-assessment experiments. DenTiUS Lab integrates DenTiUS Plaque's structure into a modular platform that isolates the user interface and the patient- and user-database from the main DenTiUS Plaque module. Figure 1 portrays a general block diagram of the complete platform, which was designed as a Content Management System (CMS). This allows clinicians and researchers to sign up, register, manage patients, and interact with DenTiUS Plaque by uploading plaque images and designing and processing experiments.

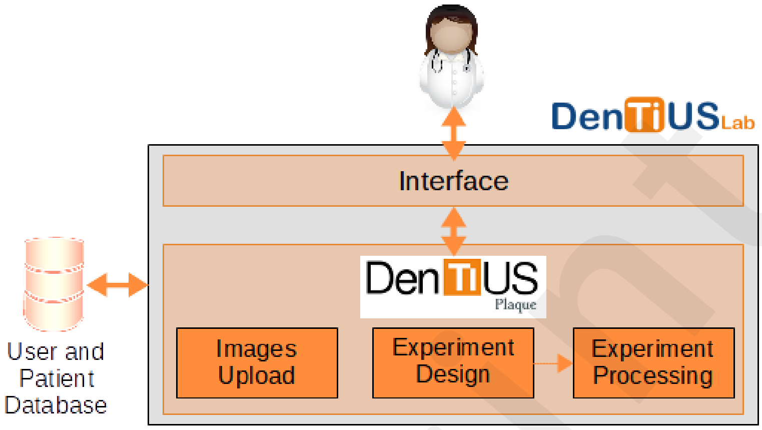

Figure 1. Block diagram of DenTiUS Plaque inside the DenTiUS global platform. The modular design facilitates the easy connection of the user and patient database to the DenTiUS Plaque tool.

DenTiUS was designed as a global platform to support clinical dental research through the inclusion of different modules that enable users to obtain a set of measures, graphs, and images with which to easily reach conclusions about their experiments. It was developed as a web application for several reasons: 1) most personal computers come with a pre-installed web browser, meaning that an installation process that could be complicated for non-specialist users is avoided; 2) platform updates (including interface improvements, bug fixes, new features, and new modules) are deployed in a process that is completely transparent, but also unintrusive. This also ensures that all users are employing the most up-to-date application, and so there is no requirement to support old versions or manage compatibility issues between them; and 3) as having a web browser is the application's only requirement, it can be used on both computers and mobile devices.

The platform was implemented as a client-server application, which runs in a central server where all the data is stored (Figure 2). All the processing tasks are carried out on the web server, and so the client does not need a high-performance device. The application logic inside the server is organized into controllers (to process user requests), services (to perform operations), and models (to manage database operations), while the well-known Model-View-Controller (MVC) pattern is used to manage entities, data access, dependency injections, and many other elements of the application.

The Java programming language was employed when developing the platform because of its popularity, power, verbosity, and how easy it is to maintain [37]. The MVC pattern, meanwhile, was constructed with the Spring framework [38], and the data storage was managed with both Hibernate [39], which is an Object Relational Mapping library, and a PostgreSQL database [40]. Image-processing algorithms were executed in OpenCV [41], specifically its Java implementation [42]. As dental images are usually very large, a limit of 5Mb was set in relation to the algorithm results to ensure accuracy, with the application resizing them automatically if required.

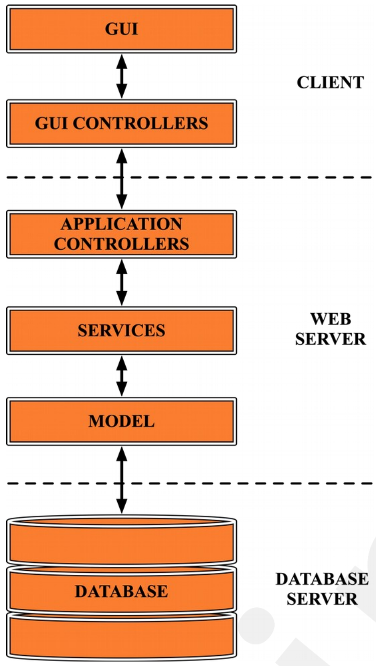

Figure 2. Structure diagram of the DenTiUS platform, which is divided into a client-side, a web server and a database server.

In summary, DenTiUS was developed with maintainability and extensibility as the main objectives. In this way, the application was implemented by following a modular structure, where the visual, logic, and data layers were isolated. The functionality in each layer was divided into classes, with many abstractions available to improve the extensibility. Consequently, the only elements requiring implementation (if necessary) to develop a new module related to dental research are: data definition (images, datasets, etc.); the description of a new kind of experiment and its processing algorithms; and a customized report format (i.e., another module with the same structure as DenTiUS Plaque, as seen in Figure 1).

The DenTiUS Lab input screen (Figure 3a) asks the user to enter the application or register. If a user is new to the system, registration is a very straightforward process, which takes only seconds to answer basic questions such as name, affiliation, and level of expertise. Once logged in, the system presents the statistics of use, namely finished processings, experiments, and patients (Figure 3b).

Every section of DenTiUS Lab is available from both the menu bar and the side menu (visible when enough space is available). Access to other utilities is also possible through the common interface bar at the top of the screen (see Figure 3). These include: a *Home* section, which is available by clicking on the DenTiUS Lab icon, and is where the operator's statistics of use are displayed; a *Help* page that explains the platform's features, the details of the processing algorithms, and examples of use; a *Downloads* section, where sample data can be downloaded for use in the application; a *User* panel (accessible by clicking on the user name), where users can change their profile data and password; and a *Language* section (English or Spanish). An *Admin* section is also available for users with administrative privileges.

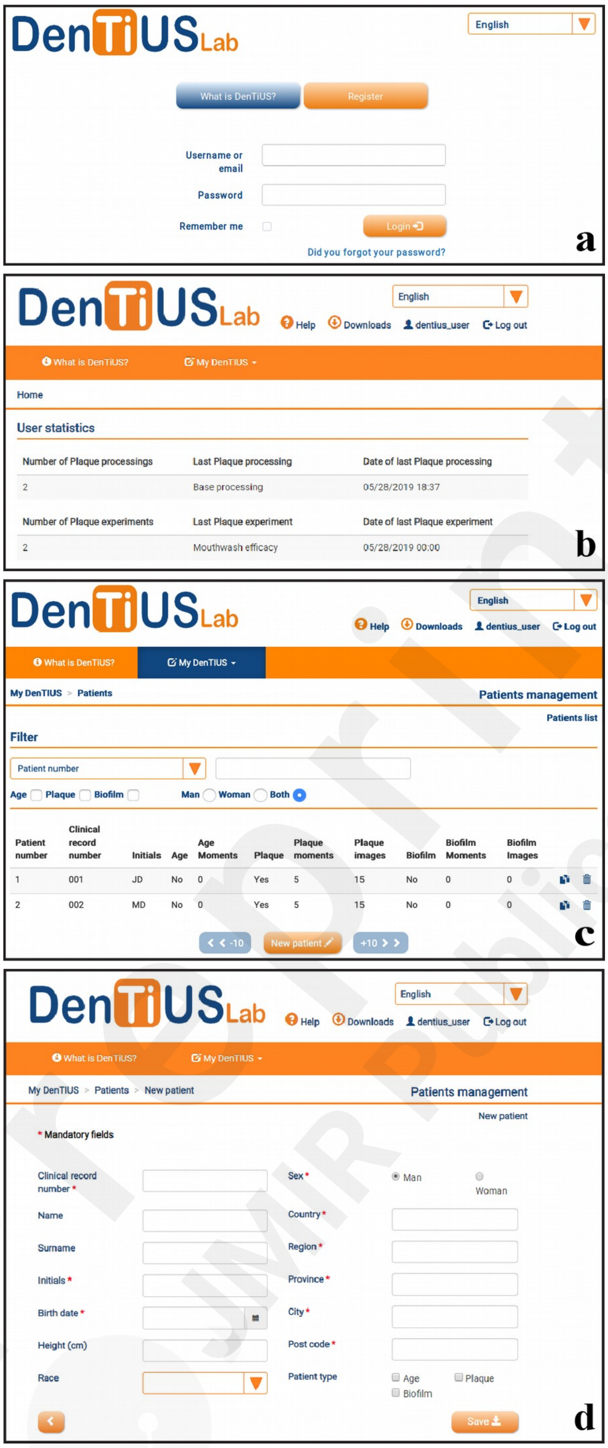

Figure 3. Common modules of the DenTiUS structure relating to users: (a) Login screen; (b) User statistics and patients: (c) Patient database. (d) New patient definition.

A *Patient* database interface (Figure 3c) allows users to register and manage their patients, who can be filtered by patient number, clinical-record number, patient initials, and sex. The user can also create new patient details by completing a form with data such as the patient's clinical-record number, birth date, race, sex, city, and country (Figure 3d). The name and surname fields are optional to preserve patient anonymity.

DenTiUS Plaque

Patient plaque images

DenTiUS Plaque was the main objective behind our development of the DenTiUS platform. The goal was to enable DenTiUS Plaque to perform as an automated Decision Support System to help experts to analyze and quantify the macroscopically-observable dental plaque deposited on teeth. In a first step, the software requires reproducible images of the fluorescein-dyed plaque taken under UV light. Fluorescein is a well-known fluorochrome in the field of dentistry and a patent for its use as a dental plaque marker was filed in the USA in 1967 by Herbert Brilliant (U.S. Patent 3-309-274; 1967). In these images, the bright blue region corresponds to the tooth area unaffected by plaque, while the green region matches plaque deposits over both the tooth surfaces and the gingiva.

To enable the assessment of dental-plaque levels at different times, an entity called a *plaque moment* was defined for a single plaque image (usually the frontal view), or a set of images (front and lateral views) captured from a patient at a particular time. The possibility of including lateral views is a novelty of the system, as these provide a better view of the posterior teeth, where more plaque is usually accumulated.

Plaque moments can be attached to a patient's file via the Patients section (Figure 3c), which contains information about each patient concerning the number of image-sets included for her/him and the number of plaque images distributed through all their moments. Another way to attach new plaque moments to a patient's record is by entering the Plaque section directly from the *MyDenTiUS* menu, where all the plaque moments are listed independently and can be modified or deleted. In any case, the user can modify, delete or include a new moment where the images (at least one) have a date, time, brief description, and optional camera set-up parameters. At this point, it is crucial to define the so-called *reference moment* or *moment 0*. This cannot be deleted, as it is used as a reference to compute the plaque-level growth over time, and usually corresponds to circumstances where there has been "perfect dental cleaning."

Plaque experiment design

The plaque experiment design module (see Figure 1) enables users to develop new experiments by selecting specific patient data and tuning the parameters of the image-processing algorithms. The experiments are presented in a list view, with several shortcuts on the right side of the screen that trigger operations like duplicating, processing, deleting or cropping the associated images. When the user creates a new experiment, a screen appears with the tabs: *New*, *Select*, *Cut Images*, and *Process*, as shown in Figure 4. Figure 4a shows the *New* tab, in which the name and description fields are mandatory. In the *Select* tab, the user must choose the plaque moments to be processed by selecting them from the patient database. The system automatically includes the reference moment related to any selected moment. The *Cut Images* tab allows the user to optionally select part of the images or delete artifacts. Finally, the *Process* tab (Figure 4b) shows a summary of the *Experiment data* and, below that, the *Processing data* parameters, with a mandatory name and description. This permits users to try different configurations of the processing parameters for the same set of images. In this screen, the expert user can employ the default parameters or change these to different values. The meanings of these parameters will be explained later in this section.

Figure 4. Plaque experiment design: Definition of a new experiment: (a) *New* tab; (b) *Process* tab, with a summary of the experiment and processing data, showing the processing parameters that will be used when pushing the "Process" button at the bottom.

The configuration of the experiment is decided by the user according to the specific circumstances (age groups, gender, single/multiple patients) and/or objectives (effectiveness of mouthwash, effectiveness of brushing devices, smoking effects, etc.). The system performs the experiments defined by the user by processing the data of all the patients and all the patient moments included in the experiment. When the experiment involves multiple moments for the same patient, the images with the selected tooth areas are subjected to a process of normalization in the number of pixels.

DenTiUS Plaque does not permit comparisons between groups, as this was not the objective of the system, but users can export all the computed parameters to manage and prepare their own statistics with no limitations.

Processing algorithms

After an exhaustive analysis of the color characteristics of each region of interest, a process is defined to segment the dental area, excluding the gingiva region: initially, the blue and red channels are added together and the result is thresholded according to a parameter fixed by the user (by default, the algorithm chooses 75% of the darkest pixels as the background and 25% of the lightest as the foreground). The isolated pixels are then removed, and a connected component analysis is performed to identify objects from that binary image. Thereafter, a set of conditions related to region size (greater than 2000 pixels, by default) and solidity (greater than 0.5, by default) are applied to remove non-dental regions. Other specific rules, which were defined to eliminate bright artifacts, are included to make the process fully automatic. All these parameters can be changed in the *Process* tab (see the *Processing data* parameters in Figure 4b).

Once the dental area is segmented, the system must perform an analysis of its values to extract and measure the dental plaque. As mentioned previously, plaque is characterized by a high green intensity, whereas the rest of the dental region has a high blue concentration. The first step is thus the detection of the (visible) plaque by analyzing the differences between the green and blue channels (equation (1)). The rest of the dental region is considered to be a first approximation of the non-visible plaque area (equation (2)).

$$P_{visible}=|G\text{-}B| \text{ for pixels with } [G\text{-}B > 0] \quad \textbf{(1)}$$

$$P_{non\text{-}visible}=|G\text{-}B| \text{ for pixels with } [G\text{-}B \leq 0 \text{ and } G>0 \text{ and } B>0] \quad \textbf{(2)}$$

where $P_{visible}$ is the visible plaque, $P_{non\text{-}visible}$ is the initial approximation of the non-visible plaque, and G and B are the green and blue channels of the dental area, respectively.

G-B dental-area histograms are included to assess how levels of dental plaque increase over time when oral hygiene stops, with the positive and negative sides corresponding to the visible (G>B) and first approximation of the non-visible plaque (G<B), respectively. Figure 5a shows an example of a 96-hour experiment, where moments were recorded every 24 hours; while Figure 6 presents the results of the different steps of the algorithm on a frontal image of a patient after 96 hours of perfect cleaning. After professional dental cleaning (moment M0), most of the histogram area corresponded to the first approximation of the non-visible plaque area (equation (2)), as its values were highly concentrated in the negative part of the graph. In the moments that followed (M1 to M4), the histogram was flattened and displaced toward the positive side, thus increasing the visible-plaque level. In the final moment (M4), four days after a dental cleaning, the largest part of the histogram was placed on the positive side of the graph, with the visible-plaque area covering most of the dental region. The main finding behind this step was the discovery and measurement of the transition area between the visible plaque and the rest of the dental region, based on the risk of plaque developing in the near future. As a result, the system performs an extra segmentation step before displaying the non-visible plaque area (as seen in Figure 6f). According to two different parameters, δ and l, the blue/green differences are thresholded to produce three different region masks in the negative part of the graph, namely: level-1 non-visible plaque (risk of being plaque in the following hours); level-2 non-visible plaque (risk of being plaque in the following days); and no-plaque (no risk of being plaque in the medium term):

$$P_{non\text{-}visible}(level1)=|G\text{-}B| \text{ for pixels with } [G\text{-}B \leq 0 \text{ and } G\text{-}B \geq \delta] \quad \textbf{(3)}$$

$$P_{non\text{-}visible}(level2)=|G\text{-}B| \text{ for pixels with } [G\text{-}B < \delta \text{ and } G\text{-}B \geq l] \quad \textbf{(4)}$$

$$noPlaque = |G\text{-}B| \text{ for pixels with } [G\text{-}B<l] \quad \textbf{(5)}$$

where the *l* parameter is automatically calculated from non-visible plaque histograms of current and reference images (Figure 5b); it is defined as the first value where the number of non-visible plaque pixels in the current image is greater than the number of non-visible plaque pixels in the reference image (moment 0).

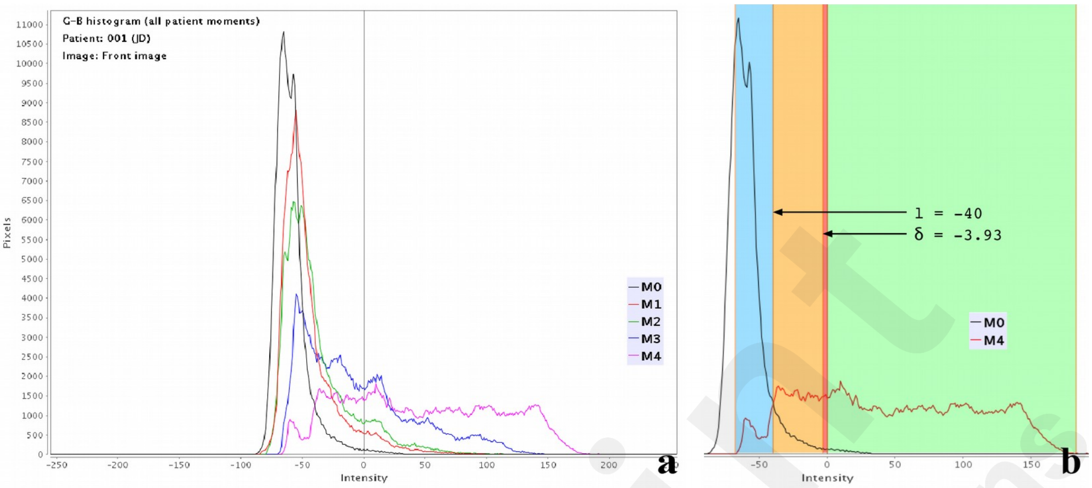

Figure 5. G-B histogram where the vertical line represents G-B=0. (a) G-B histograms for moments M0 to M4, showing the progression of the histogram values toward the G-B positive values (visible plaque); (b) Definition of l and δ for M4, showing plaque (green), non-plaque (blue), level-1 non-visible plaque (red, defined by *δ*), and level-2 non-visible plaque (orange, defined by *l*). The boundary between the non-plaque and the level-2 non-visible plaque (*l*) is easily observable in this chart, as it corresponds to the intensity value where the two histograms cross.

The *δ* parameter can be set by the user or is automatically resolved as the absolute difference between the average pixel values of the blue and green channels in the dental area. The modification of this parameter by the user in the *Process* tab (see Figure 4b) indicates an increase or decrease in the level-1 non-visible plaque region (red area in Figure 6f). This means that the pattern of plaque development can be simulated by starting with a minimum value and progressively increasing it.

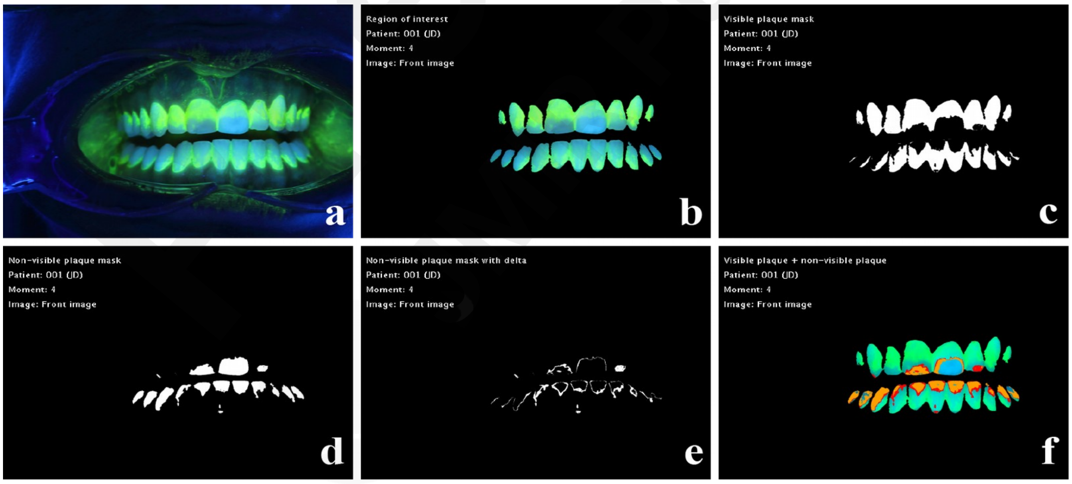

Figure 6. Results of the different steps of the algorithm relating to the frontal image of a patient after 96 hours of perfect cleaning. (a) Frontal UV image; (b) Segmented dental area; (c) Visible plaque mask; (d) Non-visible plaque mask; (e) Non-plaque level-1 mask (f) Final labeled image (blue: non-plaque; green: visible plaque; red: non-visible plaque level-1; orange: non-visible plaque level-2).

RESULTS

Plaque processing results

Figure 7 portrays the complete process for a single patient image-set belonging to a particular experiment: plaque images were uploaded to the database; the plaque experiment was designed; and

the experiment processing was launched.
When the processing finishes, the user can view the results by clicking on the appropriate notification or the *Processings* submenu. The processing results are divided into four tabbed subsections (Figure 8): *Data and properties*; *Single measurements*; *Measurements download*; and *Images and charts*. The *Data and properties* tab presents a summary of statistics concerning the processing, as well as the processing parameters. Figure 8b shows the *Single measurements* tab, which presents the results of the quantitative analysis for each image in table form, with absolute averages obtained in each image (indices about visible plaque) and relative measurements (indices about visible and non-visible plaque) relating to the reference moment. As shown in this figure, and just below the tabs with an information alert, the user must click on each image to display their processing results in the *Single measurements* and *Images and charts* tabs.
The clinical indices defined in this research provide information on the bacterial plaque on dental surfaces, in particular: the area where it is present; its intensity; a combined value between the area and intensity; and different growth parameters. The system can produce dental-plaque clinical indices in a computerized form, including in relation to: the plaque index of an area per intensity (API index, a value between 0-100); the area growth index (growth rate of plaque per unit of time in hours - percentage area/hour); and the area time index (the time, in days, needed to achieve a plaque area of 100% concerning the initial area at the same moment).

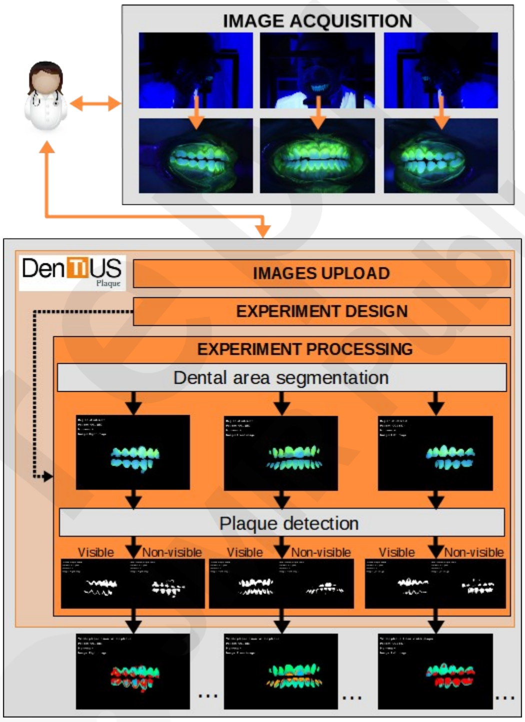

Figure 7. Process of detecting and quantifying dental plaque using DenTiUS Plaque for one patient moment in an experiment.

In the example in Figure 8, after 96 hours of plaque accumulation, focusing on the visible plaque values, the patient presented an API index of 21.18 and a hypothetical plaque growth rate of 0.75% per hour. A particularly interesting parameter supplying the labeled image is the area time. In this case, the area-time relative value is 1.67 for visible plaque and 0.61 for total plaque (see Figure 8b). In other words, from a theoretical point of view and assuming a constant growth pattern for that moment, the patient would take 1.67 days to achieve a visible plaque level of 100%. This value is obviously lower, around 0.61 days, when it comes to realizing plaque levels of 100% for both non-visible and visible plaque.
The measurement tables can be customized and downloaded in the CSV and spreadsheet formats via the *Measurements download* tab, where users can also select specific parameters within the absolute

and relative measurements.

Figure 8c portrays an example of the images, tables and charts obtained for one moment of one patient. The *Images and charts* tab provides not only the final view of the plaque regions in each plaque image, but also the intermediate results of the computer-vision algorithm, including the tooth mask, the visible-plaque mask, the difference between the blue and green channels in both the teeth and visible-plaque regions, and others. The final labeled image represents the areas with no plaque (in blue) and visible plaque (in green). Also shown are the areas that will become plaque in the short term, graduating to near-plaque (red areas, non-visible plaque level-1) and medium-term plaque (orange areas, non-visible plaque level-2).

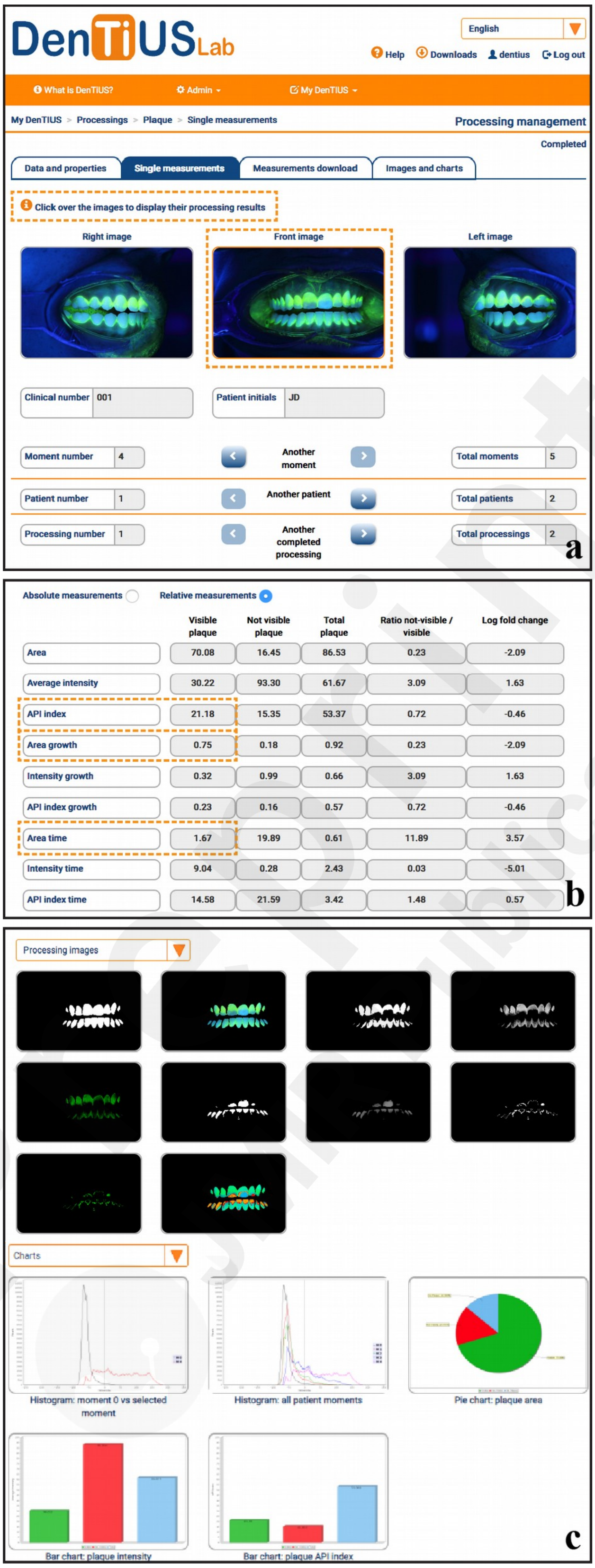

Figure 8. Processing results. (a)(b) *Single measurements* tab: the absolute (first column, visible plaque) and relative measurements (relative to the reference image) for the frontal image; (a)(c) *Images and charts* tab for the frontal image.

Pie and bar charts comparing the levels of visible plaque and non-visible plaque, as well as the non-plaque areas, are also presented. Finally, two histograms are presented that compare: the intensity distribution of the plaque in the selected image moment to the corresponding image of the reference moment; and the intensity distributions of the plaque through all the moments. A vertical line at 0 can be seen in both histograms, separating values corresponding to visible plaque (equation (1)) from those relating to non-visible plaque and non-plaque (equations (3), (4) and (5)). Finally, a full report presenting all the tables and graphs can be generated in the PDF format via the main *Processings* menu. This will contain all the processing data, including all the information described previously for each processing tab.

DenTiUS GUI usability

As with most web applications, DenTiUS has a graphic user interface (GUI) that is designed to be friendly, simple, and intuitive, as well as adaptable to the various screen sizes on mobile phones, tablets, and computers. A usability test, based on *The Computer System Usability Questionnaire* (CSUQ) [43], was proposed to assess the suitability of the GUI in real terms. This test was adapted to DenTiUS, resulting in nine questions with scores ranging from 1 (strongly disagree) to 5 (strongly agree). The questions were designed to measure the following: (Q1) overall ease of use; (Q2) workflow efficiency; (Q3) user comfort; (Q4) learning process; (Q5) productivity; (Q6) value of the error messages; (Q7) online help; (Q8) attractiveness of the interface; and (Q9) overall satisfaction.

The questionnaire was sent to 34 dentists doing research in the field of dentistry, including mainly phD researchers (82%), undergraduate research fellows in their final year of career (9%) and senior researchers (9%). The testers were given instructions about how to enter DenTiUS Lab and proceed with a test case based on a patient with plaque growth over several days. In particular, they performed the following steps: signing up to the application; registering some patients and plaque moments; defining an experiment; continuing with the processing; and searching for various results.

Figure 9 demonstrates that all the questions produced fairly good results, with a mean score of around 4 in almost all cases. The best-scoring questions were Q2, Q7, Q8 and Q9, relating to the workflow efficiency, the value of the online help, the attractiveness of the user interface, and the overall satisfaction, respectively. By contrast, some users stated that the platform errors in Q6 should be more informative and provide better solutions to fix any issues.

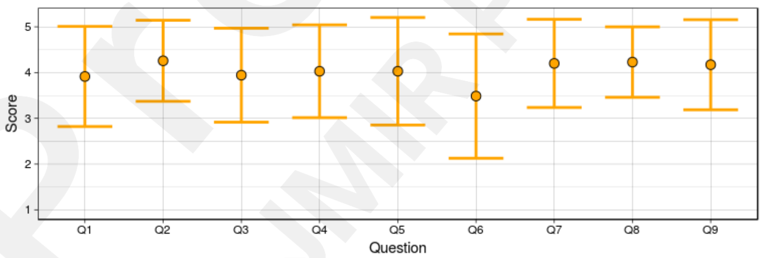

Figure 9. Score distribution of each usability test question. Each error bar represents the mean and standard deviation.

Availability of the software

Access to the DenTiUS Lab web-platform is available free of charge for non-commercial use for researchers and clinicians. Any requests to use the software should be made by sending an email to dentiuslab@gmail.com. The platform can be found at: http://tec.citius.usc.es/dentiuslab.

Discussion

Principal Findings

It is well known the importance that dental plaque has in the etiopathogenesis of important oral diseases, such as caries and periodontitis [5, 44]; and on the other hand, the recognized limitations of conventional clinical indices of dental plaque quantification [20, 23] which are widely used both in clinical and research settings. Therefore, in order to improve the diagnosis of dental plaque, it is essential to develop new computer systems that allow the objective quantification of dental plaque levels.

This paper introduces DenTiUS Plaque. This is a tool for the quantification of bacterial plaque and is integrated into a general web-based platform with a common management process for users and patients.

DenTiUS is the first dental-research system to enable: image collections and patient data to be managed; experiments to be designed; and images with a customized configuration to be automatically processed. The developed tool produces accurate and repeatable results for the assessment of clinical indices of bacterial plaque levels relating to a patient, or group of patients, over time, ensuring the sustainability of the process in terms of the time and effort required by users of the system. Clinical users with no technical background can process the images in batches and obtain a table of measurements (most of which have been specifically produced for this platform) and explanatory graphs that can be exported in various formats (PDF report, spreadsheet and JPEG images). Although a more complex final report could be designed, these different outputs were a requirement identified by dental researchers to enable them to have access to all the values needed to produce their own statistics.

Specifically, a novel algorithm was developed in DenTiUS Plaque to detect and quantify dental-plaque levels from UV images. This approach first detects the dental region, and then segments and quantifies visible plaque by analyzing the difference between green and blue channels. Initially, DenTiUS Plaque could represent a tool that offers the following advantages over the QFL-D system [33-35]: The first advantage is that DenTiUS Plaque allows detecting different areas in the remaining dental regions according to the risk of them developing plaque in the future; this finding was referred to as "non-visible plaque". DenTiUS Plaque provides the detection and quantification of non-visible plaque at two levels: the probability of becoming visible plaque in the short term (level-1) or medium term (level-2). The second advantage is that DenTiUS Plaque not only provides indexes of plaque quantification (the API index) as the QFL-D system but also indexes to measure the plaque growth pattern over time for a given patient such as the area growth index and the area time index. In addition, all the clinical indices developed at DenTiUS Plaque are applicable to both quantifying visible and non-visible plaque levels.

Regarding the usability test carried out on people working in the dental field, overall, the users stated that they were likely to use the application in the future, with the results revealing that DenTiUS Plaque was suitable for its ultimate purpose.

Biological coherence between conventional clinical indices and new indices derived from image analysis is a study to be carried out to test the validity of the latter [24, 45, 45]. In this sense, our research group used an *in situ* five-day bacterial plaque growth model to conduct some initial experiments on the validity of the DenTiUS Plaque clinical indices, comparing the results with those obtained with a conventional clinical index; in order to obtain both types of indexes, the plaque was stained with fluorescein and displayed by ultraviolet light [44, 48]. Concerning the degree of correlation between the conventional and the API indices, days one, two and three of plaque formation revealed very high correlations between the two approaches (Spearman's Rho $\geq$ 0.770). However, in the days where there was little or excessive accumulation of bacterial plaque, days 0 and four, respectively, the relationship between the two measurement systems was suboptimal (Spearman's Rho $\leq$ 0.540), evidencing the limitations of the conventional index and the convenience of applying the API version produced by DenTiUS Plaque for these clinical situations. An interesting objective of future research would be to apply both, the DenTiUS Plaque and the QFL-D system, on the same group of patients to quantify the levels of dental plaque, verifying the correlation between both systems.

Limitations and future work

Further work will be conducted to improve the platform. Additional help will be included in the software based on the results of a GUI validation exercise.

The image cropping system will be improved to exclude unwanted artifacts in the image automatically. More research tools will be fully integrated into the DenTiUS platform. An example is DenTiUS Biofilm, which will enable the quantification of microscopic dental plaque, as well as comparisons of the plaque growth pattern at the microscopic (biofilm) and macroscopic levels (plaque), taking advantage of the shared management of patients and users.

Conclusions

The DenTiUS software allows an automatic, reliable and repeatable quantification of dental plaque levels, providing information about area, intensity and growth pattern. Its application in the analysis of plaque evolution patterns associated with different oral conditions, as well as to evaluate the effectiveness of various oral hygiene measures, can represent an improvement in the clinical setting and the methodological quality of research studies.

Acknowledgements and declarations

Ethical approval: Images from Spanish Caucasian subjects are part of a study protocol approved by the Galician Clinical Research Ethics Committee (registration number 2014/008). The image collection was performed following the ethical standards of our institution's research committee and the 1964 Declaration of Helsinki and its later amendments [49].
This work has received financial support from Johnson & Johnson company (Grant 2016-CE219), Consellería de Cultura, Educación e Ordenación Universitaria (accreditation 2019-2022 ED431G-2019/04, 2017-2020 Potential Growth Group ED431B 2017/029, 2017-2020 Competitive Reference Group ED431C 2017/69, and N. Vila-Blanco support ED481A-2017) and the European Regional Development Fund (ERDF), which acknowledges the CiTIUS-Research Center in Intelligent Technologies of the University of Santiago de Compostela as a Research Center of the Galician University System.
Author's contributions: The whole work was supervised by MJ Carreira and I Tomás. N Vila-Blanco, V Freire, C Balsa-Castro and MJ Carreira designed and implemented the whole platform; MJ Carreira, C Balsa-Castro and I Tomás supervised the implementation, designed the image processing algorithms and defined the clinical indices.

Conflicts of Interest

None declared.

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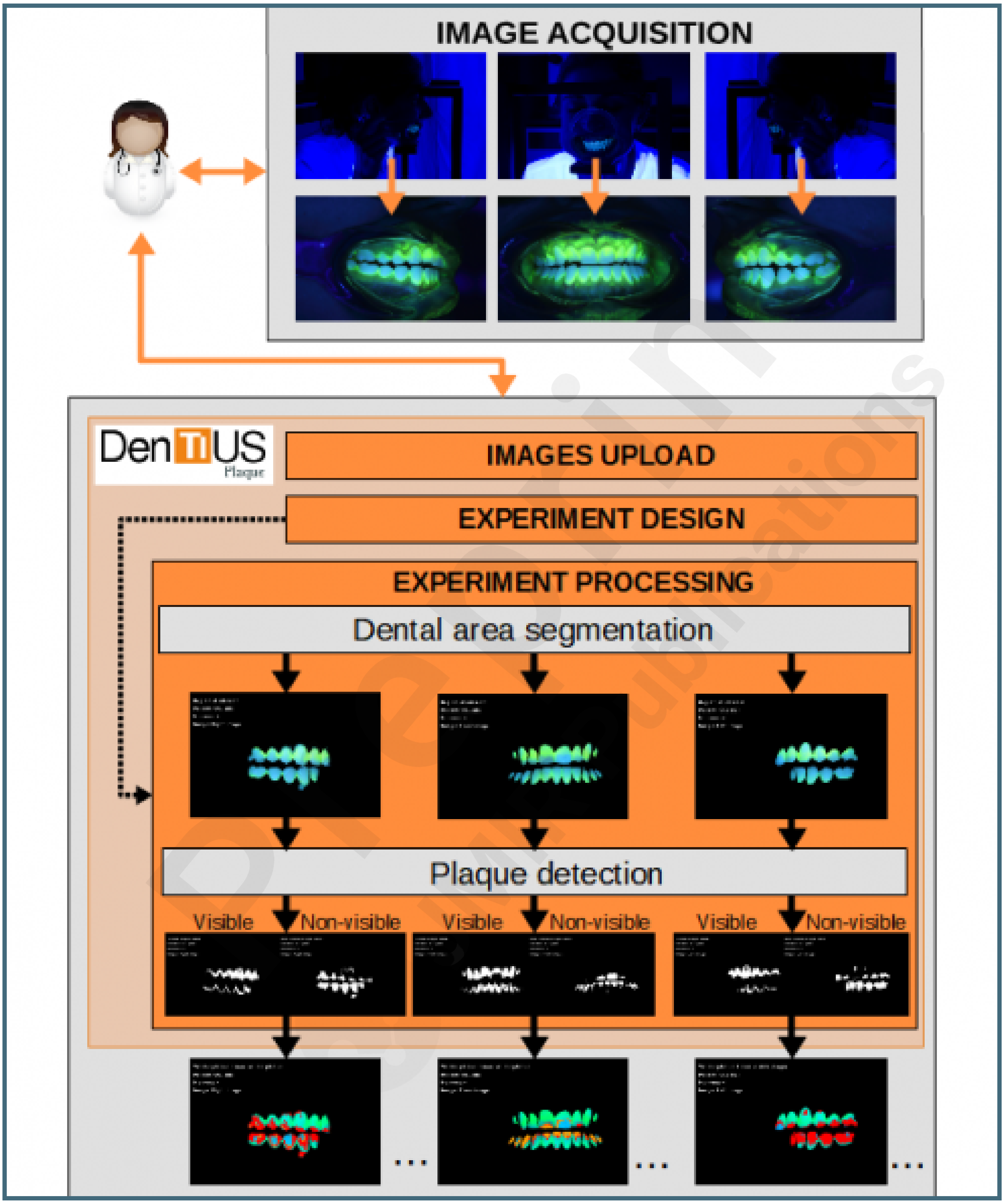
Supplementary Files

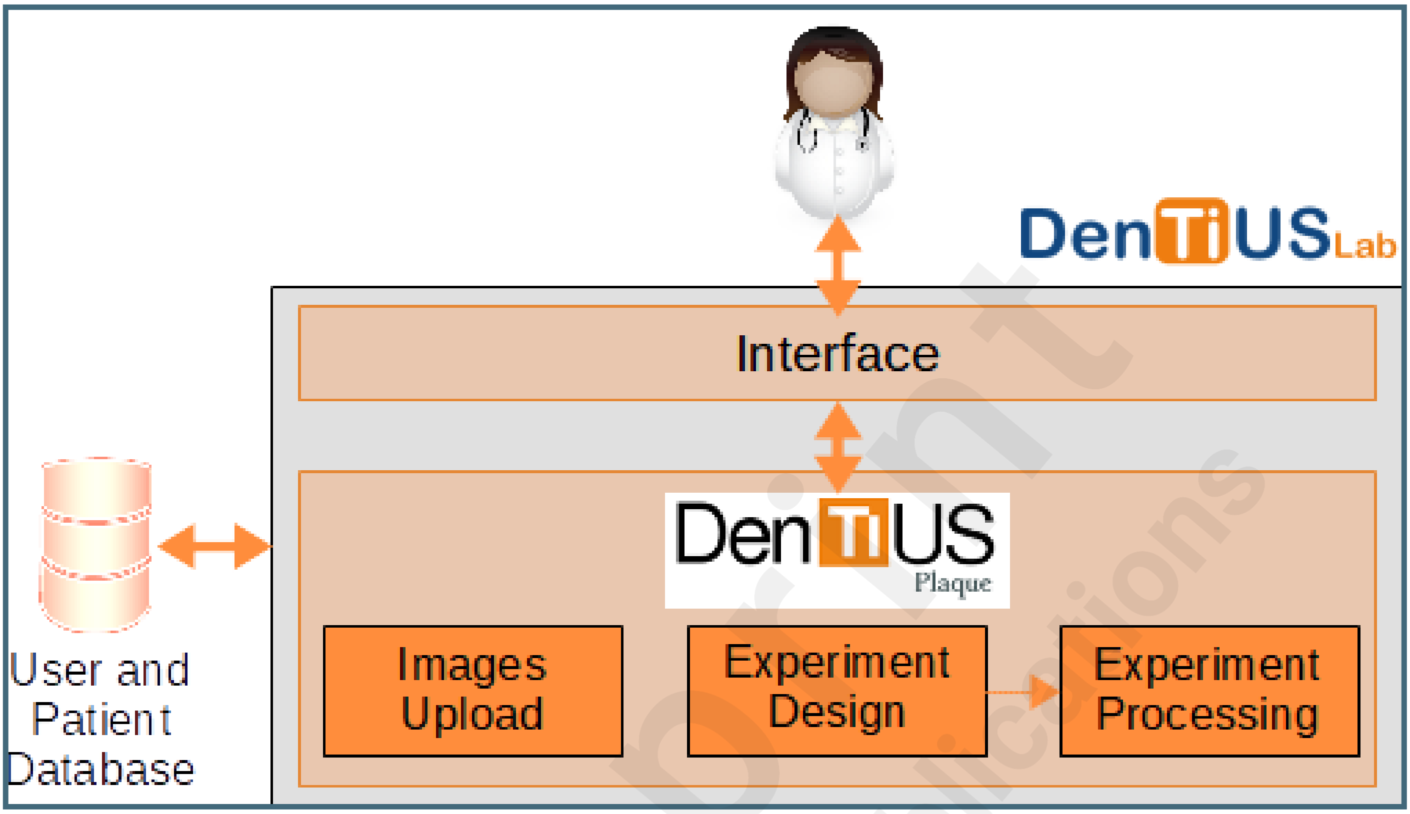
TOC/Feature image for homepages

Process of detecting and quantifying dental plaque using DenTiUS Plaque for one patient moment in an experiment.

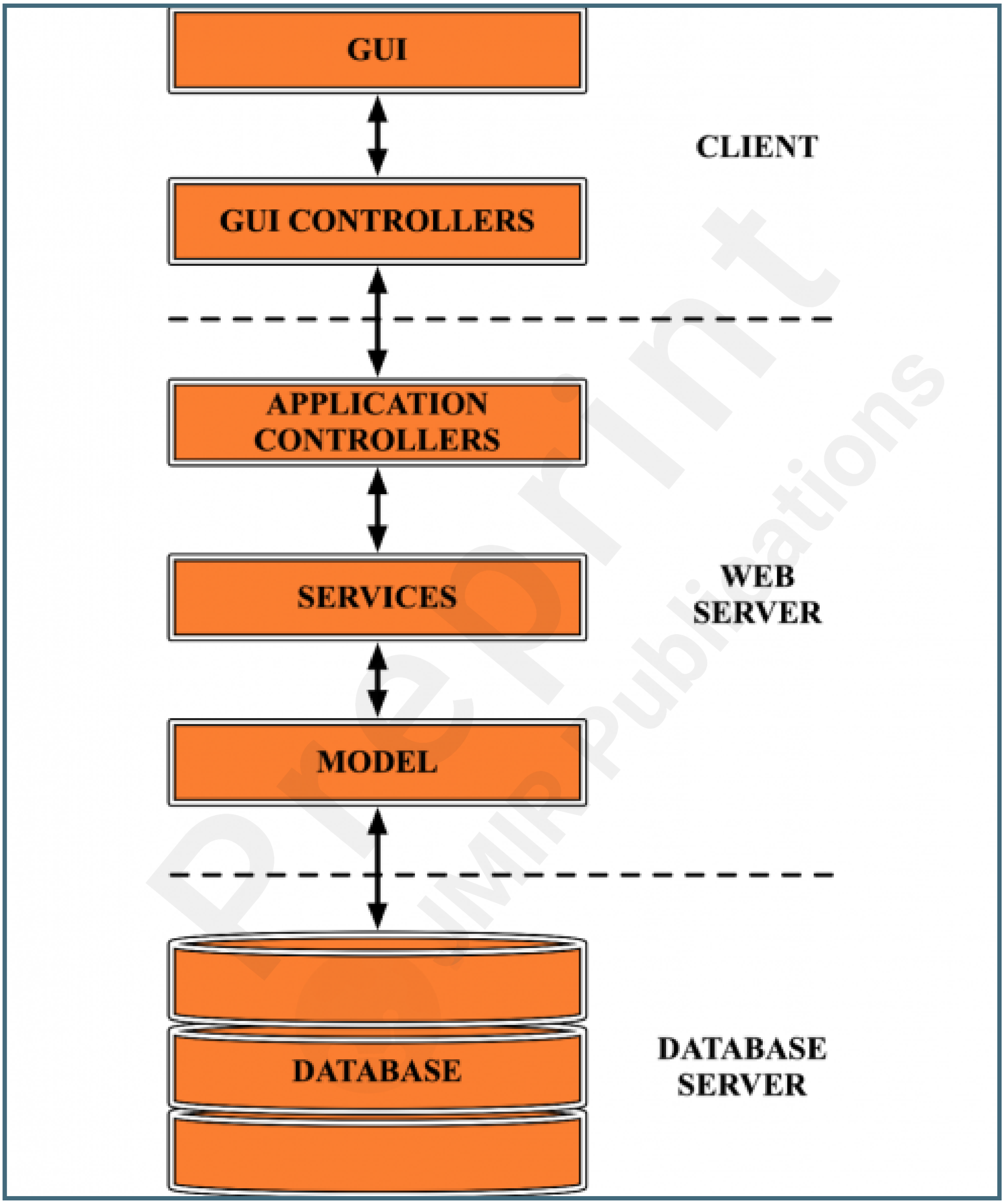


Figures

Block diagram of DenTiUS Plaque inside the DenTiUS global platform. The modular design facilitates the easy connection of the user and patient database to the DenTiUS Plaque tool.



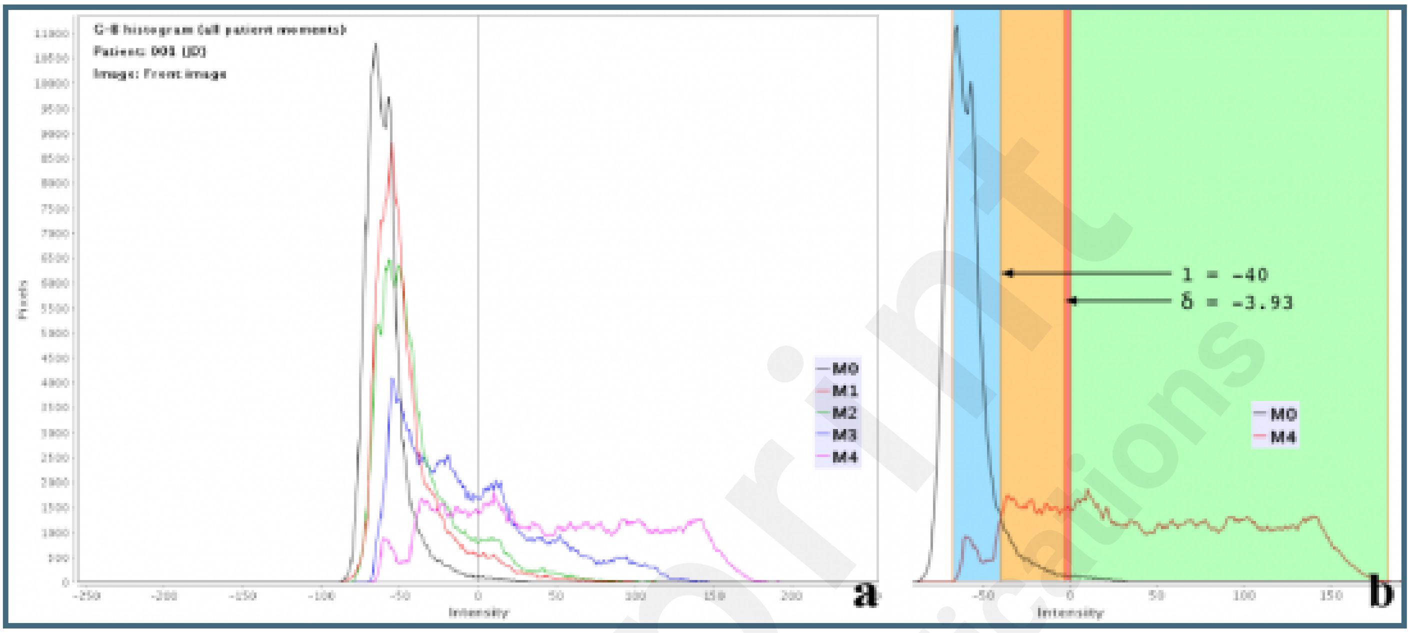
Structure diagram of the DenTiUS platform, which is divided into a client-side, a web server and a database server.



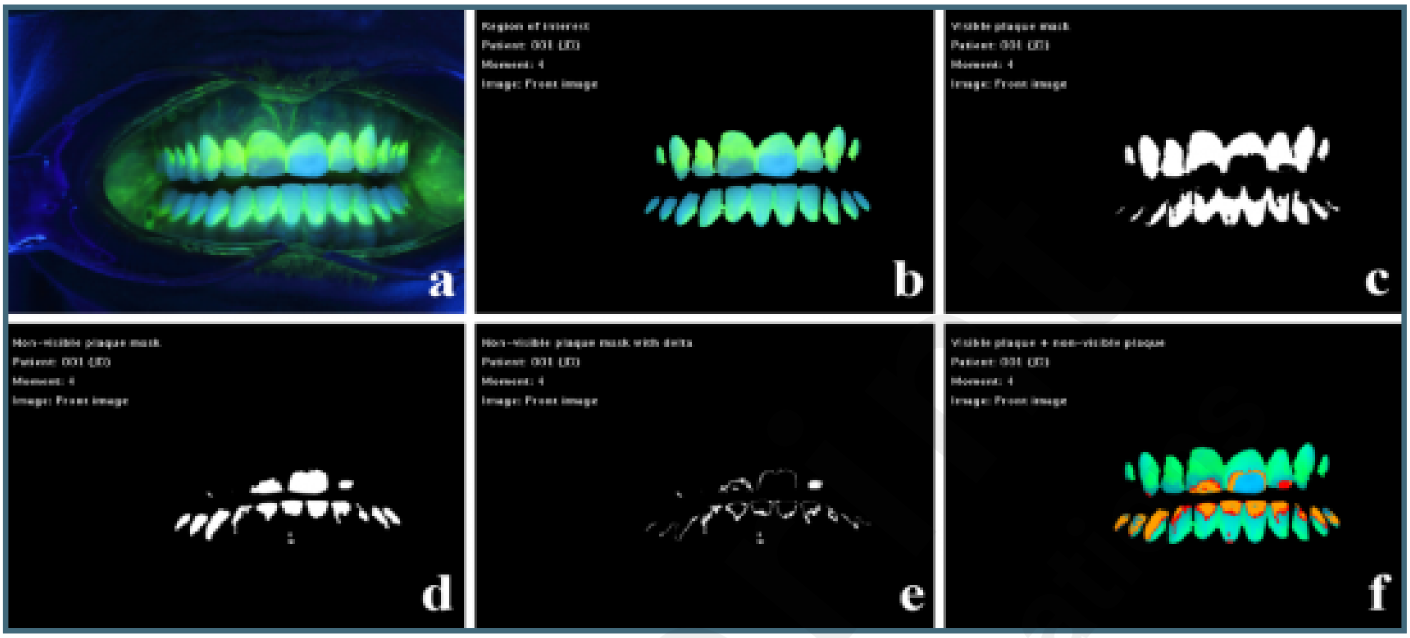
Common modules of the DenTiUS structure relating to users: (a) Login screen; (b) User statistics and patients: (c) Patient database. (d) New patient definition.

Plaque experiment design: Definition of a new experiment: (a) New tab; (b) Process tab, with a summary of the experiment and processing data, showing the processing parameters that will be used when pushing the "Process" button at the bottom.

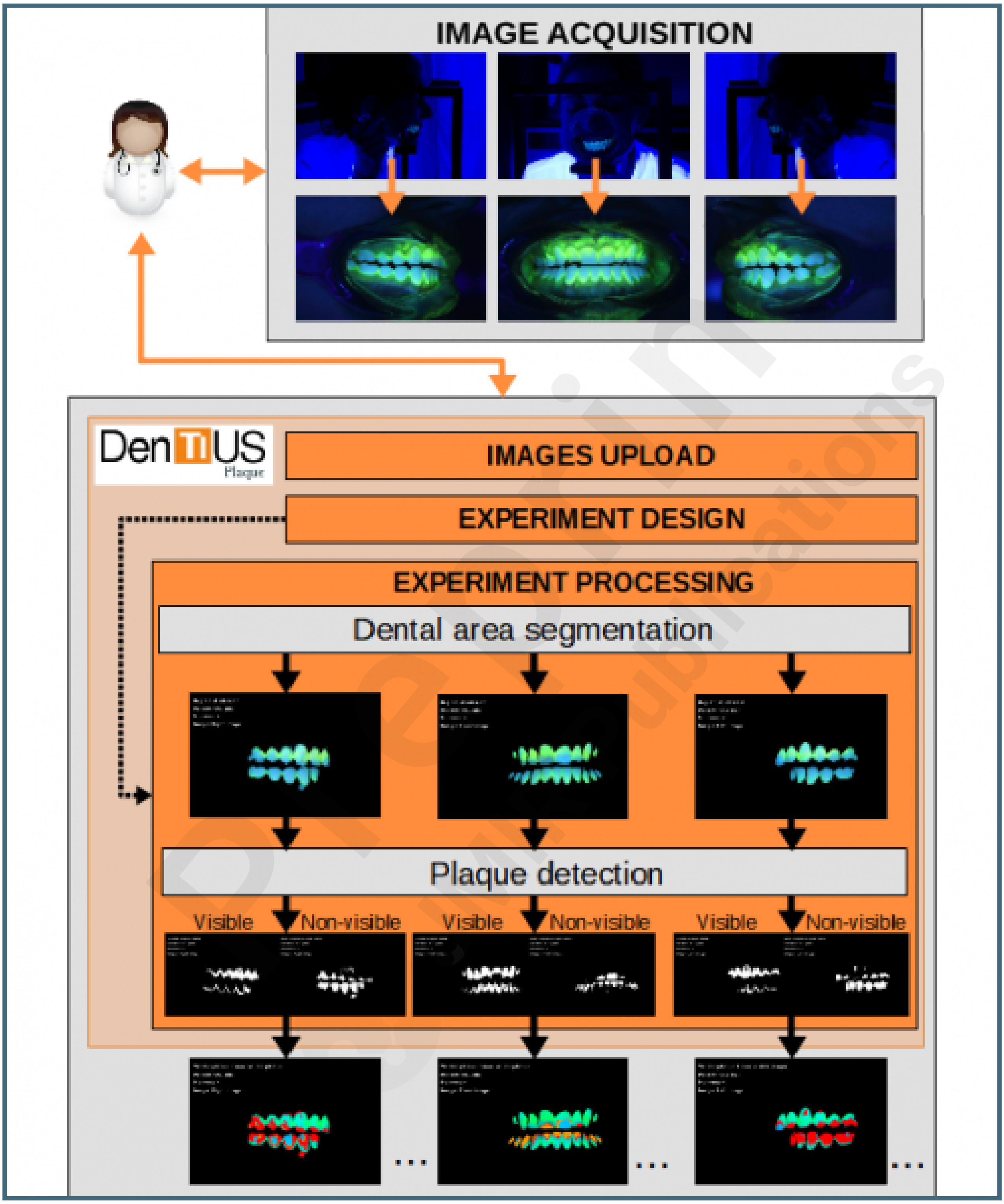
G-B histogram where the vertical line represents G-B=0. (a) G-B histograms for moments M0 to M4, showing the progression of the histogram values toward the G-B positive values (visible plaque); (b) Definition of l and ? for M4, showing plaque (green), non-plaque (blue), level-1 non-visible plaque (red, defined by ?), and level-2 non-visible plaque (orange, defined by l). The boundary between the non-plaque and the level-2 non-visible plaque (l) is easily observable in this chart, as it corresponds to the intensity value where the two histograms cross.



Results of the different steps of the algorithm relating to the frontal image of a patient after 96 hours of perfect cleaning. (a) Frontal UV image; (b) Segmented dental area; (c) Visible plaque mask; (d) Non-visible plaque mask; (e) Non-plaque level-1 mask (f) Final labeled image (blue: non-plaque; green: visible plaque; red: non-visible plaque level-1; orange: non-visible plaque level-2).



Process of detecting and quantifying dental plaque using DenTiUS Plaque for one patient moment in an experiment.



Processing results. (a)(b) Single measurements tab: the absolute (first column, visible plaque) and relative measurements (relative to the reference image) for the frontal image; (a)(c) Images and charts tab for the frontal image.

Score distribution of each usability test question. Each error bar represents the mean and standard deviation.