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A new software for dimensional measurements in 3D endodontic root canal instrumentation

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Summary. The main issue to be faced to get size estimates of 3D modification of the dental canal after endodontic treatment is the co-registration of the image stacks obtained through micro computed tomography (micro-CT) scans before and after treatment. Here quantitative analysis of micro-CT images have been performed by means of new dedicated software targeted to the analysis of root canal after endodontic instrumentation. This software analytically calculates the best superposition between the pre and post structures using the inertia tensor of the tooth. This strategy avoid minimization procedures, which can be user dependent, and time consuming. Once the co-registration have been achieved dimensional measurements have then been performed by contemporary evaluation of quantitative parameters over the two superimposed stacks of micro-CT images. The software automatically calculated the changes of volume, surface and symmetry axes in 3D occurring after the instrumentation. The calculation is based on direct comparison of the canal and canal branches selected by the user on the pre treatment image stack.

Key words: microtomography, endodontic root canal instrumentation, digital imaging analysis.

Riassunto *(Un nuovo software per la misura delle dimensioni tridimensionali nel trattamento dei canali radicolari)*. Per ottenere misure dimensionali nello spazio 3D delle modificazioni occorse a causa del trattamento endodontico è necessario sovrapporre le immagini relative alle scansioni di microtomografia computerizzata (micro-CT) effettuate sul dente prima e dopo il trattamento. Il nuovo software realizzato permette di ottenere informazioni quantitative dall'analisi di immagini di micro-CT del canale dentale dopo il trattamento endodontico. Specificatamente tale software è in grado di trovare la migliore sovrapposizione tra le immagini relative al dente prima e dopo il trattamento in modo analitico usando il tensore di inerzia del dente. La strategia scelta per realizzare tale sovrapposizione ha permesso di evitare l'uso di procedure di minimizzazione che possono portare a risultati diversi sulla base dell'esperienza dell'utente e possono richiedere un elevato tempo di calcolo. Le misure dimensionali sono state quindi ottenute tramite la analisi contemporanea delle due strutture sovrapposte. Il software calcola automaticamente i cambiamenti che si sono avuti all'interno del canale quantificando le variazioni di volume, di superficie e la modifica dell'asse del canale a seguito del trattamento endodontico. L'analisi viene eseguita tramite confronto diretto del canale e delle diramazioni del canale selezionate dall'utente sulla serie di immagini che caratterizzano il dente prima del trattamento.

Parole chiave: microtomografia, lavorazioni canalari endodontiche, analisi immagini digitali.

INTRODUCTION

The main objective of root canal therapy is thorough shaping and cleaning of all pulp spaces and its complete obturation with an inert filling material [1].

Although successful endodontic therapy depends on many factors, one of the most important steps in any root canal treatment is canal preparation. This is an essential step because proper preparation determines the efficacy of all subsequent procedures. Root preparation includes mechanical debridement, creation of space for delivery of medicaments, and the creation of optimal canal geometries for adequate obturation [2].

The thorough removal of debris by means of mechanical instrumentation is one of the primary objectives in endodontics and aimed at accomplishing the total elimination of remaining pulp tissue and microorganisms from the root canal system [1].

A major cause of endodontic failure is the inability to locate, debride, or obturate properly all canals of the root canal system [3].

Together with diagnosis and treatment planning, a better knowledge of the root canal system and its frequent variations is an absolute necessity for a successful root canal treatment [4-6].

A further aim of root canal preparation is to

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achieve a progressive and uniform conical shape within the canal. To allow complete cleaning, shaping and obturation of the entire root canal space. Anatomical variability of the teeth is often an issue in root canal treatment.

The Bramante technique, based on serial sectioning and scanning electron microscopy [7], modified by Kuttler *et al.* [8] offers a method that is relatively easy and economic and provides information of the three-dimensional (3D) action of an instrument in the canal space.

A more accurate information can be obtained by X-ray micro computed tomography (micro-CT) [9, 10].

Micro-CT allows to obtain very high quality 3D images of specimens [11] and thanks to the non-destructive character of micro-CT it is possible to repeat the experiment before and after any sample treatment to evidence modification of the 3D sample structure.

The use of proper software in combination with tomographic techniques gives the possibility to realize a virtual material laboratory [12] to investigate real complex structures and predict mechanical properties and failure behaviour of bulk materials and composites under stress [13, 14], characterize homogeneity and interfaces [15], predict fluid flow in porous media and the accessibility of drugs or other molecules and calculate permeability of the materials [16]. From these examples is clear that micro-CT data acquisition and 3D volume reconstruction are often the starting point of more quantitative analysis [17, 18].

There are several commercial and academic software developed for general image processing and for many different analysis targeted to a particular research area but to our knowledge there are not yet available suites targeted to the quantitative analysis of tooth and endodontic comparative studies.

In this paper we describe a custom software allowing to evaluate quantitative parameters by comparison between the pre and post endodontic treatment 3D structures revealed by micro-CT scans. The lack of user friendly tools which can help dentists to easily have quantitative results is probably an obstacle which reduces the application of micro-CT in dentistry more than the instrumental availability [19].

Specifically, the software developed and presented here can help researchers to compare 3D tomography reconstruction obtained before and after endodontic instrumentation.

Quantitative information are obtained with direct comparison of the surface of the canals before and after treatment in a common reference system. In this way, if the endodontic treatment has left some zones of the canal the visual inspection of the acquired 3D structures should show the complete superposition between them. The untouched zones can then be more easily recognized but to quantify their surface can be still an hard task.

More generally we can say that micro-CT, as magnetic resonance imaging (MRI) and other non destructive imaging techniques, have the unique potentiality of allowing the *in silico* comparison of real 3D structures of samples before and after some modifications occur. The software package developed so far includes some other algorithms to estimate the percentage of untouched canal surface, the volume of dentin removed by mechanical debridement and the modification of the root canal axe in the 3D space.

MATERIALS AND METHODS

An interesting publication [20] reported on a study conducted on curved root canals in molars using the anatomic endodontic technology (AET) technique, and recommended against its use in curved canals. Unfortunately the authors tested an early and no longer available version of the AET system. Significant changes had been made more than three years prior to their publication. The rigid stainless steel transition files that were used after shaping the middle third were eliminated as they transported too much. The shaping files originally taken to full length are now used to within 3 mm of the apex. Additionally, a change in apical shaping files to a triangular cross-section, to be used to working length, considerably reduced the early transportation problems. As a result of these changes the validity of their data and conclusions are no longer valid. In fact, further research conducted with the same methodology demonstrated that AET instruments were able to prepare both maxillary and mandibular molars with optimal results and low risk of procedural errors [21].

The authors evaluated root canal morphology in a freshly extracted human molar treated with one of the most used instrument in endodontics and assessed the results by means of micro-computed tomography scanner (SkyScan 1072, SkyScan, Kartuizersweg, Belgium). Sample was scanned before and after root canal preparation.

The scanning procedure was completed using 10 W, 100 kV, 98 µA, a 1 mm-thick aluminum plate and 15x magnification with 5.9 s exposure time and 0.45° rotation step, resulting in a pixel size of 19.1 µm x 19.1 µm.

The acquisition procedures consisted in the realization of several two-dimensional (2D) lateral projections of the specimen during the 180° rotation around the vertical axis. This digital data were further elaborated by reconstruction software that obtained new axial cross sections with a pixel size of 19.1 µm x 19.1 µm. The distance between each cross-section was 38.0 µm. Three-dimensional root canal models were reconstructed and evaluated for volume. The total volume of dentine removed and the volume of the coronal, middle and apical third of each root canal were calculated. The mean volume change before and after instrumentation was determined for the entire root canal as well as for each section. A qualitative evaluation of root canal preparation was performed on the three-dimensional models.

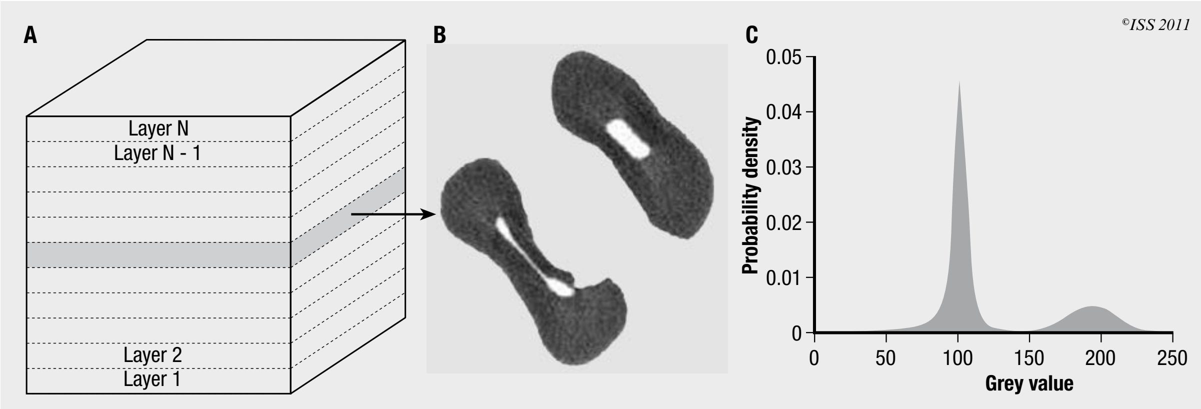

Fig. 1 | *Result of micro-CT scan of a tooth.*
A: the tooth is graphically presented as 400 (conjoined) 2D layers with each layer composed by 1024 x 1024 cubic voxels; B: the grey value distribution for each layer is related to the absorption coefficient of each voxel; C: probability density function of the absorption coefficient within the investigated tooth.

Data analysis

Pre-processing of the images

MicroCT data are the collection of X-ray attenuation coefficients of all the voxels which compose the 3D structure. The attenuation coefficient is proportional to the electron density of the materials and hence it is roughly proportional to the local mass density of the sample.

The micro-CT images are preliminary segmented to distinguish between different materials phases. This delicate process should be done carefully especially in the case of composite materials and if the aim is the characterization of interfaces [22, 23].

The histogram shown in *Figure 1C* is the probability function of the density of one tooth obtained from micro-CT data set. The left peak refers to voxels with low attenuation coefficient, which represent the void spaces (inside and outside the tooth structure), the right peak is related to voxels with higher attenuation coefficients which belong to the tooth structure.

The study of root canal is essentially the characterization of void space inside the tooth.

The algorithm here used for segmentation considers voxels with attenuation coefficient higher than a chosen threshold to be part of the tooth and includes in the tooth structure also voxels with a value 10% lower than the chosen threshold if they are neighbours of voxels which satisfy the threshold.

Superposition of the pre and post treatment structures

Images obtained before and after treatment do not overlap since the original sample holder of the ×-ray microfocus CT scanner does not allow the user to insert the sample with a chosen position and orientation in the micro-CT apparatus with a resolution better than the scanning one. The 3D structures of the tooth shown in *Figure 2* evidence the mismatch of the data structure as obtained after the scan and segmentation process. The same mis-

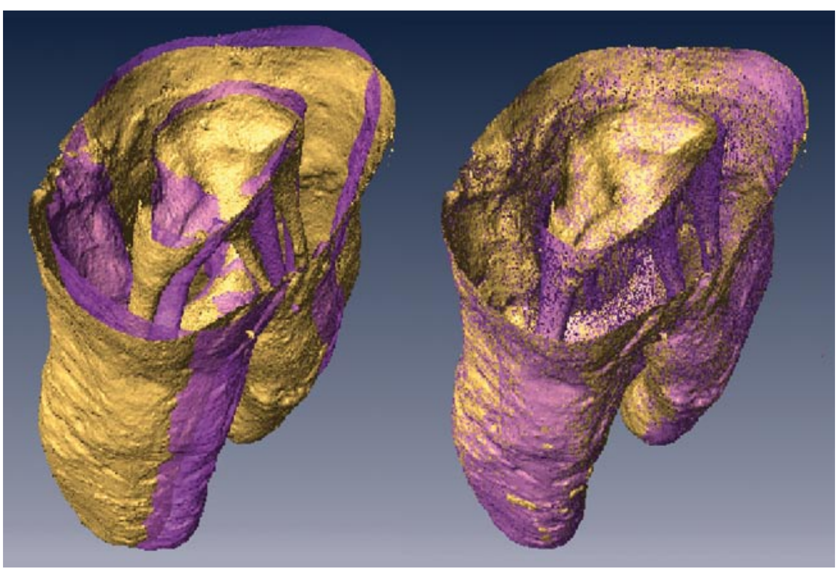

Fig. 2 | *Left side: original 3D reconstruction of the two acquired structures; right side: the two structure have been superimposed using the developed algorithm.*

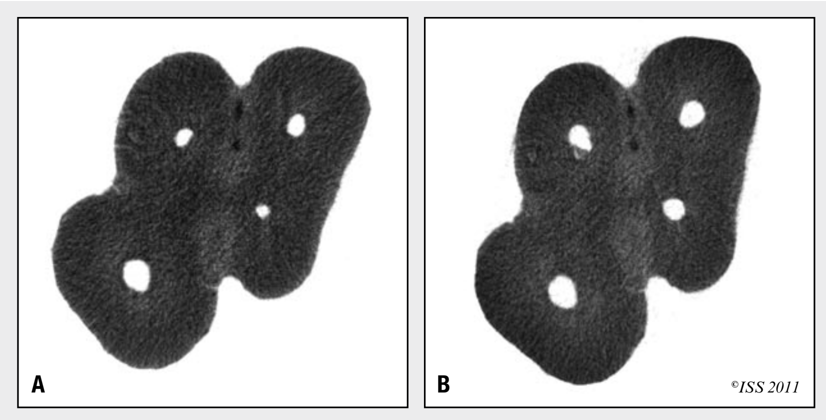

Fig. 3 | *A: original 2D image of pre-treatment slice; B: the corresponding slice acquired after treatment not yet co-registered.*

match naturally occurs in the corresponding stack of 2D images, as reported in *Figure 3* as example. The co-registration algorithm developed for this task is based on the calculation of inertia tensor as reported in classical mechanics [24] and it is able to automatically find the best superposition between the two images of the tooth. Bergman and co-workers [19] used a minimization approach to find the best superposition between two scans of the same tooth. The procedure is based on the maximization of Mutual Information [25] which is a functional based on the information content that one variable contains about another variable. Mutual Information of the image intensity values of corresponding voxel pairs is maximal if the images are geometrical aligned. In general the solution achieved by minimization algorithms depends on an initial set of parameters selected by the user and this process can be time consuming other than user dependent. The minimization procedure is necessary in other biomedical contexts, such multi resolution or multimodality co-registration. Conversely here, for the purpose of endodontic application, we developed an analytical and more straightforward approach. The external surface of the two structures is a zone which it can be often affected by artefacts, for this reason the developed algorithm uses the entire tooth volume and not only its boundaries. The endodontic co-registration algorithm developed is based on pure classical mechanics of rigid body. We model the tooth as an homogeneous object with all canals filled by the same homogeneous material and we apply classical mechanics of rigid body assuming that the inertia ellipsoid of the two structures should be identical in the reference system of their centres of mass. After a rigid translation of the post structure to superimpose the two centres of mass the inertia tensor is calculated and diagonalized. This procedure gives two sets of 3D vector, that are the free axis of rotation of the pre and post treatment structures, which are two independent orthonormal basis of the 3D space. The sequence of three rotations necessary to superimpose the two sets of vector can be calculated analytically and it is the same sequence of rotation necessary to obtain the superposition of the two structures [24].

As already stated the inertia tensors are calculated using the whole volume of the tooth, it is possible to apply the same method considering only the two external tooth surfaces. In this way computer calculation time is reduced but if the external surfaces are affected by some artefacts the quality of superposition can be less accurate. The software package allows the user to choose the desired strategy, bulk or external surface superposition and yields one new set of reoriented slices of the post structure which can be overlapped to the pre structure. Additionally, if the two spatial resolutions of the two scans were different the software creates the output slices on the basis of the lower resolution between the two.

Canal axis tracer

The comparison between pre and post treatment canal axis is the goal of this software tool. An algorithm has been developed to find the canals inside the tooth structures following their branches and trace the curvilinear abscissa of the canal axe along its path. This algorithm is not really optimized for automatic use and the best performance is obtained if the user provides few inputs to the software selecting the canal of interest and the branch direction to follow when needed. The algorithm look for the canal in the two co-registered structures in a parallel way and calculates the pattern of the canal axe (data not shown). The changes in the canal axe pattern after endodontic treatment are sometimes minimal, while for other canals the changes are really important especially when the rectification of the canal occurs.

Quantification of canal volume and surface

The pre and post treatment canal axe can be very different. The comparison between the canal geometry and in particular between the pre and post treatment canal surface is based on new cal-

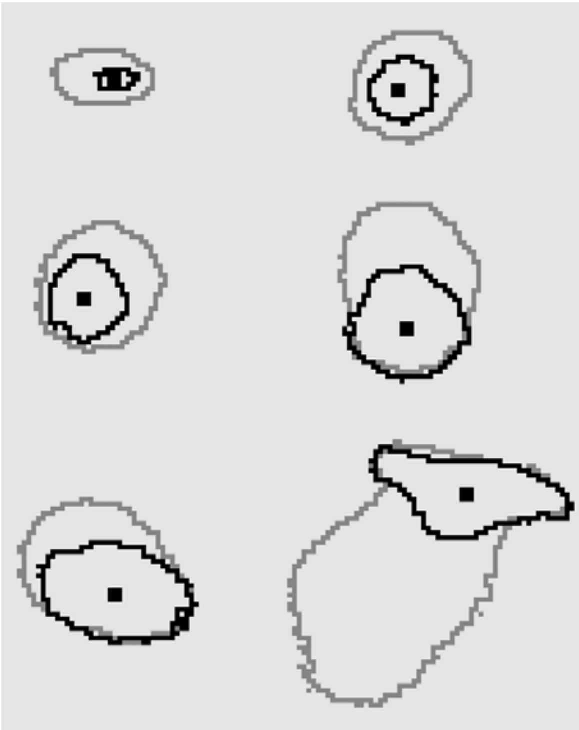

Fig. 4 | *Canal border evaluated perpendicularly to the canal curvilinear abscissa in six different points along the selected canal. The position of the six chosen points has been calculated as the distance of the centre of mass of the canal slice from the exit point of the canal in proximity of the root apex. The pictures show the structure of the canal before treatment in black and its centre of mass with a black square, together with the shape of the canal border after treatment in gray. Top-left image corresponds to a distance of 2.5 mm from the exit point, top-right 5.0 mm, middle left 6.0 mm, middle right 8.00 mm, bottom left 10.0 mm and bottom right 12.0 mm.*

cu lated slices with the same thickness as the original ones but oriented perpendicularly to the pre treatment canal axe. As a result the pre and post treatment corresponding canals are really depicted in a common reference system and the enlargement of the sections of the canal along its curvilinear abscissa is easily visualized *(Figure 4)*.

The software package allows the user to select one canal and produces the slices as reported in *Figure 4*. It is possible to choose the desired distance between two consecutive slices to be cut along the evolution of the canal axe.

The software obviously compares the pre and post treatment canal and automatically calculates the quantity of dentin removed for each new section using the known voxel size and estimates the percentage of untouched surface as in *Figure 5*.

The percentage of untouched canal surface is very important to characterize the goodness of the root canal preparation and it should be lower as possible for a good endodontic treatment.

The software helps the user to recognize untouched surface zones and using the pattern of the canal axe the user will be able to calculate any desired correlation, *i.e.* correlate the curvature radius (second derivative of the canal axe pattern) and the local percentage of untouched surface or correlate the presence of critical zones such as curves, constrictions, bifurcations with the quantity of dentin removed.

RESULTS AND CONCLUSIONS

The possibility to change traditional 2D characterization technique based on serial sectioning with three dimensional morphological reconstruction can give high advantage and improvements. The spatial resolution of 3D imaging technique is constantly in-

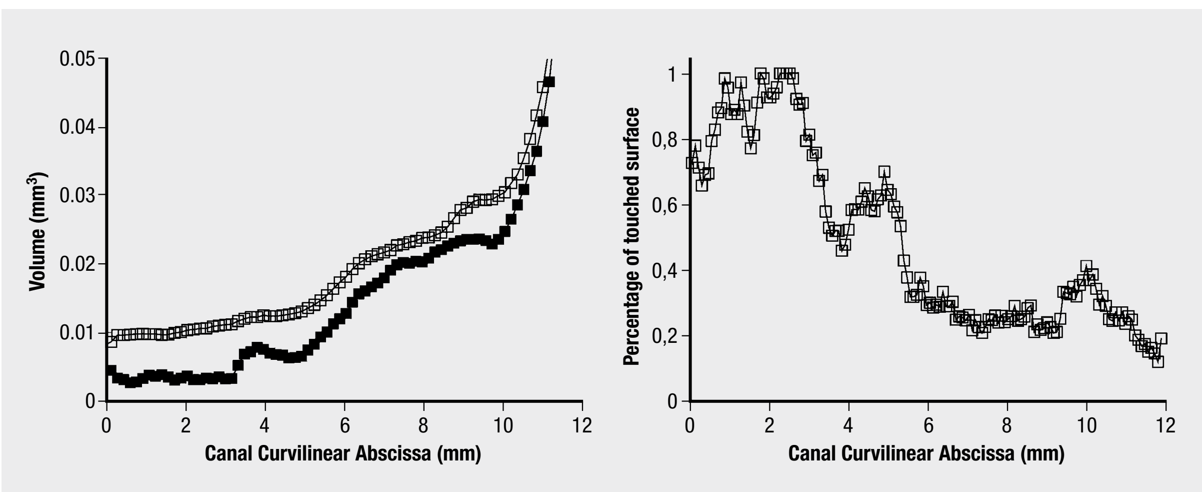

Fig. 5 | *Left frame: volume of the canal section perpendicularly to the curvilinear abscissa, filled square is the pre-treatment analysis, empty square is the post. Note that the thickness of each slice is 40 µm, in 10 mm there are 250 slices; right frame: percentage of touched canal surface along the axe.*

creasing and micro-CT offers also some very interesting application such as phase contrast and chemical characterization. In particular X-ray micro-CT based on cone beam instruments recently reached a sub-micrometer resolution and allows to characterize the structural properties of a bulk material with high data fidelity in a non destructive way.

The information obtained with this instrumentation about the 3D structure of a bulk material is becoming comparable with image quality of transmission electron microscopy performed on materials sections.

Of course a non destructive laboratory technique which allows to characterize bulk materials at the nanoscale is not still available, but micro-CT, used in this study, is retained to be a good compromise between resolution and instrumental laboratory availability [11].

The difficulties to overcome are not only related to the set-up of tomographic experiments but also to the reconstruction and analysis of the 3D data structure obtained. The development of new software and new imaging technique, which can be specialized in this direction, is really critical to observe the behaviour of complex biological structure and compare the quality of new and future biomedical treatments also in very different area. The methodology described in this paper should be able to reduce technical difficulties in quantitative evaluation of changes occurred in teeth after any treatments, and particularly in endodontics. The main modules of the software, the co-registration and the segmentation, can be used in a different research context. The endodontic case here described can be viewed as a case study and more general problem in dentistry and medicine can be faced starting from the use of these two algorithms for further high specific analysis and quantitative evaluation.

Conflict of interest statement

There are no potential conflicts of interest or any financial or personal relationships with other people or organizations that could inappropriately bias conduct and findings of this study.

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