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SHORT COMMUNICATION

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Volumetry of human molars with flat panel-based volume CT in vitro

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Abstract The flat panel-based volume computed tomography (fpVCT) is a new CT device applicable for experimental, three-dimensional evaluation of teeth at a resolution of about 150 μm in the high contrast region. The aim of this study was to investigate whether fpVCT was suitable for quantification of the volumes of dental hard tissues and the root canal system to establish a new method for morphological studies. Fifty-two extracted third molars (maxillary: 31, mandibular: 21) were examined with a prototype of an fpVCT using a volumetry algorithm at different levels according to the radiographic density of enamel and dentine. Volumetry of the root canal system was performed after "region growing segmentation": starting from a voxel in the centre of the root canal, this algorithm searches voxels of same density in the surrounding. The volumetry of the root canal system was stopped by the investigator at the apical constriction. Results showed that dentine, enamel and root canal system could be well distinguished in three-dimensional images. Volumetry yielded the following data (cm^3, mean±SD): dentine 0.438±0.111, enamel 0.227±0.051, root canal system 0.052±0.017 and total volume 0.753±0.159. In conclusion, the fpVCT is appropriate for non-destructive volumetry of large numbers of teeth in experimental laboratory studies.

Keywords Molars · Volumetry · CT · fpVCT · Morphology

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Introduction

A detailed understanding of the complexity of root canal systems is imperative to ensure successful root canal therapy. Even detection of anatomical details in extracted teeth is of interest [6, 7, 22]. In the examination of root canal preparation techniques [18, 20, 21] as well as in general anatomical studies, not only non-destructive three-dimensional exploration but also accurate volumetry of the different dental structures is of considerable interest.

Conventional destructive approaches used in the past for three-dimensional reconstruction of the root canal were based on extensive wax- or computer-based reconstructions of histological cuts [3, 12]. More appropriate, non-destructive, three-dimensional evaluation of dental structures is possible with magnet resonance tomography (MRI) [2, 3, 11]. STRAFI (stray field imaging) represents a special modification of MRI used in dental research in previous studies [1, 3]. However, radiographic approaches are more common such as computed tomography (CT), but due to their low resolution of 500 μm, conventional CT systems are not sufficient for detailed investigation or volumetry of dental structures [29]. Indeed, tuned aperture computed tomography (TACT), based on several two-dimensional dental radiographies acquired from different angles with a digital detector, allows three-dimensional reconstruction of teeth [13, 14], but the images are of low quality compared to other techniques and volumetry is not feasible. In contrast, micro-CT allows detailed exploration of teeth and volumetry of root canals at a resolution of up to 36 μm, but due to the small size of the gantry and the long scanning time of up to 6 h, the application of the method is limited to single extracted teeth [17, 20, 21, 23–25].

A new approach in dental clinical computer tomography is the Accuitomo system (Morita, Tokyo, Japan) based on a cone beam X-ray CT. It is suitable for radiographic evaluation of a localised cylindrical area of the head at a spatial resolution of about 2 line pairs per millimeter. The radiation dose is similar to a conventional panoramic radiography. Possibly, the system is appropriate for volumetry of dental hard tissues, though there are no publications on this topic in the literature [6].

The flat panel-based volume computed tomography (fpVCT) is a new, experimental CT system offering the opportunity to explore complete arches or skulls at a visibility of about 150 μm in the high contrast region, which is superior compared to conventional CT systems [7, 10, 15, 16, 27, 28]. The system is based on new detector technology and has been adopted in several experimental approaches for pre-clinical, three-dimensional evaluation of very small structures such as non-invasive, high-resolution monitoring of tumour angiogenesis [10, 15, 16].

Advantages of the system are the high isotropic resolution and an efficient quantum yield at a very fast sequence of the images along with a gantry of more than 40 cm in diameter [7, 10, 15, 16]. Due to the high resolution with isotropic voxels, there are distinctly less partial volume effects than in conventional CT systems [7].

In a laboratory study, suitability of fpVCT for visualization of teeth and root canal systems has already been shown [7]. Even lateral canals, communications of root canals and denticles can be visualised three-dimensionally. Furthermore, in an ex vivo study, fpVCT was adopted for visualization of incomplete and complete vertical root fractures [6, 7] but volumetry of dental tissues was not performed until now.

Due to the limitations of previous methods, only few data on the different volumes of dental structures are available. Therefore, the aim of the present pilot study was to establish the fpVCT for non-destructive volumetry of dental structures considering third molars as examples.

Materials and methods

Specimens

Fifty-two extracted human upper and lower third molars were evaluated in the study. The teeth were extracted in the clinical routine and were evaluated anonymously. Directly after extraction, the teeth were stored in a formalin solution (5%). Thirty-one upper and 21 lower molars were enrolled in the study, including 22 fully erupted, 21 partially retained and 9 fully retained teeth. The mean average age of the subjects in the study amounted to 22.1±8.0 years.

Flat panel-based volume CT

Three-dimensional analysis and volumetry of the extracted teeth were performed with a prototype of a flat panel volume detector CT (fpVCT, GE, Global Research Centers, Niskayuna, NY, USA) [6, 7].

The gantry contains an X-ray tube (Performix 630, GE Medical Systems, New York, NY, USA) and two flat panel detectors. The X-ray tube has a focus of 0.7 mm at a maximal voltage of 140 kV and a current of up to 400 mA. One scan is performed in about 8 s.

Both flat panel detectors have a dimension of 20.5×20.5 cm. The detectors contain a diode array made of amorphous silicon (a-Si) covered by a layer of thallium dotated caesium iodide (Tl:CsI). The sensor array is composed of 1,024×1,024 single elements. The pixel size amounts to 200×200 μm. Due to the radiographic enlargement of 1.43, the spatial resolution amounts to 150 μm; 3.6 line pairs are read out per millimeter. Data were reconstructed on a 512×512 matrix resulting in a final voxel size of 45 μm. A modified Feldkamp algorithm was used for reconstruction of the data.

After acquiring data, image reconstruction and volumetry were performed with a special software for evaluation of the datasets (voxtools 3.0.64 AW4.2, GE Centers, Niskayuna, NY, USA) at an Advantage Windows Workstation (GE Centers, Niskayuna, NY, USA).

Volumetry

Adequate colours, opacity and contrasts were defined for the depiction of the teeth and their different hard tissues according to the HU (Hounsfield units) [6, 7]. Volumetry was carried out with a volumetry algorithm at different levels according to the radiographic density of enamel and dentine. A threshold value of 1,200 HU was adopted for evaluation of dental hard tissues in general. Volumetry and evaluation of dentine were performed at a level of 1,485–2,750 HU to reduce partial volume effects to the greatest possible extent. Enamel was measured at >2,750 HU.

Volumetry of the root canal system was performed after “region growing segmentation”: starting from a voxel in the centre of the root canal, this algorithm searches voxels of same density in the surrounding. The volumetry of the root canal system was stopped by the investigator at the apical constriction. This was necessary because the lumen of the root canal system was filled with air. Accordingly, differentiation towards the surrounding was difficult. This was especially true for teeth with incomplete formation of the root.

Artefacts on the root surfaces were edited by the investigator before volumetry.

Statistical evaluation

Due to the lack of normal distribution, statistical evaluation of significance was performed with the Mann–Whitney test. The level of significance was set at $p<0.05$. Statistics were calculated using the software package Statistika 6.1 (StatSoft, Tulsa, OK, USA). Statistical comparisons were conducted between upper and lower molars as well as between molars of different eruption status.

Results

With fpVCT, enamel, dentine and root canal system could be distinguished well from each other in three-dimensional views as shown exemplarily for some teeth (Fig. 1). Only single views of the three-dimensional images are given. Evaluation of the teeth from different points of view in different cuts is possible for complete, three-dimensional exploration of the teeth.

Volumetry was carried out for all of the 52 teeth. The mean volume of enamel was 0.227±0.051 cm^3 over all teeth. For the dentine, 0.438±0.111 cm^3 was recorded, for the root canal system, 0.052±0.017 cm^3, and for the total volume, 0.753±0.159 cm^3. Dental hard tissues had a mean size of 0.700±0.155 cm^3.

Teeth from maxilla and mandible were evaluated separately (Table 1). Total volume and volume of enamel in upper jaw teeth were significantly lower compared with mandibular third molars ($p<0.05$). For the dentine, no differences were observed between upper and lower jaw teeth. However, the root canal system had a significantly higher volume in mandibular than in maxillary teeth.

Also, the influence of the level of retention on partial and total volumes was investigated (Table 2). No significant differences were observed between these types of samples.

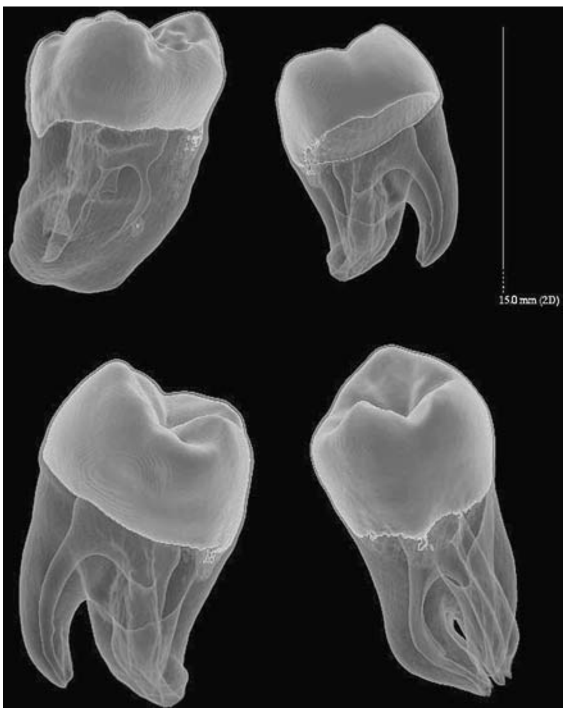

Fig. 1 fpVCT images of third molars. Clear distinction between enamel, dentine and root canal system

Discussions

The fpVCT seems to be appropriate for non-destructive volumetry of dental structures as shown in the present study exemplarily for human third molars. Main advantage of the system is the non-destructive approach at a high resolution which allows detailed exploration of the teeth [6, 7, 10, 15, 16]. Previous investigations on fpVCT yielded that very small structures such as incomplete vertical root fractures as well as denticles or side canals can be evaluated precisely at a resolution of 150 µm [6, 7]. Possible applications of fpVCT-based volumetry are experimental studies on root canal preparation techniques. Furthermore, it is of interest for non-destructive morphological investigation of certain teeth such as primary or dysplastic teeth. Also, comparative quantification of substance loss during different preparation techniques for indirect restorations is conceivable.

However, general problems of CT systems have to be kept in mind such as partial volume effects. It is necessary to know these sources of errors to avoid overinterpretation of the generated three-dimensional reconstructions [19, 20]. The segmentation process which is the prerequisite for the volumetry overemphasises sharp edges as there is a yes or no decision for the certain voxels. Accordingly, the volumes of the root canal and of single dental hard tissues may be underestimated depending on the different Hounsfield units defined for the certain structures. In addition, side canals smaller than the voxel size or the resolution, respectively, are not detectable. Any details appear sharper than in reality [19, 22]. Indeed, volume of total hard tissues was determined to be a little bit higher than the addition of the data acquired separately for enamel and dentine would suggest.

However, to the knowledge of the authors, there are as yet no studies investigating the volumetric distribution of the different hard tissues in teeth. Accordingly, it was difficult to find a gold standard for precise, non-destructive,

Table 1 Volumes of all mandibular and maxillary third molars, (n=52), MV±SD

	Volumes of all third molars (cm^3)	
	Maxilla (n=31)	Mandible (n=21)
Enamel	0.207±0.039	0.255±0.054
Dentine	0.425±0.111	0.456±0.111
Root canal system	0.044±0.012	0.064±0.016
Total volume	0.714±0.142	0.811±0.167

Table 2 Volumes of all third molars according to level of retention, (n=52), MV±SD

	Volumes of all third molars (cm^3) according to level of retention		
	Fully retained teeth (n=22)	Partially retained teeth (n=21)	Completely erupted teeth (n=9)
Enamel	0.222±0.040	0.240±0.063	0.208±0.039
Dentine	0.396±0.086	0.476±0.132	0.451±0.082
Root canal system	0.049±0.020	0.056±0.014	0.051±0.014
Total volume	0.699±0.121	0.811±0.194	0.749±0.104

three-dimensional volumetry of dental hard tissues to estimate the accuracy of the new fpVCT method.

A well-established laboratory system successfully used for experimental exploration and volumetry of teeth especially in endodontic studies is the micro-CT [18–22, 24]. Based on special three-dimensional root canal models, several root canal preparation techniques were evaluated. By that means, changes in volume, surface area and diameter of the root canals were recorded during instrumentation of the root canal quantitatively, but volumes of the dental hard tissues enamel and dentine were not determined separately [19, 20, 22]. Superimposed pictures allow comparison of unprepared and shaped root canals [18–21]. With an isotropic resolution of up to 34 µm, the micro-CT system is superior compared to fpVCT, but in other points, fpVCT is advantageous [20, 21]. Due to the size of the gantry, many teeth can be scanned at the same time, whereas micro-CT allows evaluation of single teeth only [6, 7, 20, 22]. Furthermore, a long scanning time up to 6 h is required when working with micro-CT as improvements in resolution are always reflected in a long scanning time [19, 20, 22]. With fpVCT, a scanning process takes less than 10 s due to the new detector system based on a diode array made of a-Si covered by a layer of Tl:CsI meaning quite a good resolution at a very short scanning time [6, 7, 10, 15, 16].

A limiting factor for possible clinical application of the fpVCT system is the lack of variable collimation of the X-ray tube in the prototype used in the study despite the fact that the CT dose index amounts to 0.172 mGy/mAs which is comparable to MDCT systems permitted for clinical use. The radiation dose of a CT examination of the head amounts to 120 mSv, while the radiation dose of a dental radiography is 3 mSv. Accordingly, the radiation dose of a complete fpVCT evaluation of the skull is too high, but if radiation dose is minimised drastically by a more localised application of the X-ray beam to the area of interest, then future clinical applications of the fpVCT detector technology are feasible for endodontic purposes [6, 7].

Other possible problems of the method used in the present study are small structures detected on the root surfaces having the same density compared with enamel (Fig. 1). For precise volumetry of the enamel, these structures had to be edited. They represent possibly thick layers of cementum, hypercementosis or enamel pearls [23]. Hypercementosis is especially observed on retained or inoperable teeth such as third molars [8, 9]. This corresponds to the macroscopic observations in the present study.

An additional disadvantage of the method is that the cementum in general cannot be differentiated from dentine (Fig. 1). The cementum is a mineralised but inhomogeneous connective tissue. There are up to five different types of cementum differing in composition, thickness, function and localization [9]. The mean thickness of the cementum differs between 76 and 215 µm according to the age of a patient [30]. At an age of about 22 as in the present study, the mean thickness of the cementum amounts to 111±5 µm which is lower than the resolution of the fpVCT [28]. Due to this fact, it is impossible to differentiate thin cementum layers from underlying dentine.

The present study investigated volumes of upper and lower third molars of different grades of eruption as caries-free teeth of this type are available in larger numbers. As expected, the volumes of dental hard tissues are not related to the eruption status of third molars.

However, there were significant differences between upper and lower molars emphasizing the morphological differences of maxillary and mandibular teeth. Third molars of the upper jaw are of significantly smaller size than mandibular third molars. In contrast, another study found that upper and lower molars are approximately of the same size with respect to the total volume [26]. However, the observed mean values measured in that study of 0.773±0.162 for upper molars and of 0.776±0.140 cm^3 are in the same range as observed in the present study.

Partial volumes of third molars were investigated seldom. Mean volumes of the root canal system between 23 mm^3 for lower and 31 mm^3 for upper molars were recorded [4], which were distinctly less than the observed in the present study. However, there was no information on the grade of eruption and on the age of the patients, factors with significant impact on the volume of the root canals and the pulp chamber. Other studies on root canal anatomy describe canal volume scores varying from 5 to 9.25 mm^3 for single root canals of molars [5, 19].

Conclusion

The present pilot study shows that the fpVCT allows non-destructive volumetry of dental tissues in large numbers of teeth.

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