Examination of Grey Value Accuracy and Improvement of Image Quality in Cone Beam Computed Tomography (CBCT)

Theses of the Ph.D. Dissertation

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1 Introduction

During scientific experiments with various types of vacuum tube equipment, the discovery of X-rays in 1895, by the Bavarian physicist Conrad Röntgen, represented a major breakthrough. When X-rays were discovered, they found their way to medical applications within months. The birthday of the Dental Radiograph is set at January 1896 by German dentist Otto Walkhoff. In 1972, Godfrey Hounsfield constructed the first Computed Tomography (CT) equipment. In 1989, the first spiral CT became available. Further work in the direction of Multi Slice CT (MSCT) or Multi Detector CT (MDCT) was developed. The following types of new equipments were produced: in 1998 four slices; in 2001 16 slices; and in 2004 64 slices. Cone beam computed tomography (CBCT) was originally developed in 1982 for angiography. More than a decade later, it was applied to dentomaxillofacial diagnostics. Finally, in 1997, the first dental CBCT equipment was manufactured. It was marketed in 1998 ('NewTom'; an abbreviation of 'new tomography'). The main advantages of dental CBCT are relatively high-resolution acquisition and, compared with conventional CT, lower radiation doses with smaller and less-expensive equipment. This imaging technique is focusing on the bony structures of the head and neck region. In Hungary, we also have had the option of applying this technology since 2006.

2 Aims

The purpose of the present dissertation is the examination of the grey value accuracy and the improvement of image quality in dental CBCT. These investigations involved the pre-processing and the processing work-flow in order to minimize the technical limitations and thereby maximize the quality of the reconstructed image. This purpose was motivated in accordance with the *as-low-as-reasonably-achievable*

(ALARA) principle which is a world-requirement in the 21st century. Consequently, the radiation dose for dental patients should be optimized to achieve the lowest practical level to address a specific clinical situation. For this reason, it is of considerable importance that we obtain the best necessary image quality on a certain radiation level. The possibility of achieving the above goals have been examined by investigations summarized in the following three **Research Topics**:

- **A** minimizing the noise in the reconstructed dental CBCT image;
- **B** reducing the presence of artefacts;
- **C** improving the image quality by obtaining more accurate grey values in the reconstructed image.

The study of these three **Research Topics** materialised in four scientific publications (**Papers 1-4**).

Eight **Thesis Points** have been established which are related to the three **Research Topics** and four **Papers** in the following way:

1 Minimizing the noise in the reconstructed dental CBCT image (**Research Topic A**).
*Conditions established by drastic mass reduction in the field of view (FOV) (**Paper 1**).*

2 Minimizing the noise in the reconstructed dental CBCT image (**Research Topic A**).
*Conditions established by calibration of the detector and reaching its steady-state temperature during the warming-up period (**Paper 2**).*

3 Minimizing the noise in the reconstructed dental CBCT image (**Research Topic A**).

*Conditions established by using a more accurate reconstruction algorithm (**Paper 4**).*

4 Reducing the presence of artefacts (**Research Topic B**).

*Conditions established by calibration of the detector and reaching its steady-state temperature during the warming-up period (**Paper 2**).*

5 Reducing the presence of artefacts (**Research Topic B**).

*Conditions established by determining and then employing the ideal contrast material concentration during the procedure of mapping of the angiosome (**Paper 3**).*

6 Improving the accuracy of grey values in the reconstructed image (**Research Topic C**).

*Conditions established by drastic mass reduction in the FOV (**Paper 1**).*

7 Improving the accuracy of grey values in the reconstructed image (**Research Topic C**).

*Conditions established by calibration of the detector and reaching its steady-state temperature during the warming-up period (**Paper 2**).*

8 Improving the accuracy of grey values in the reconstructed image (**Research Topic C**).

*Conditions established by using a more accurate reconstruction algorithm (**Paper 4**).*

3 Materials and Methods

The three factors, which reduced the quality of dental CBCT image, were covered in the three research topics examined. The experiments carried out and summarized in this dissertation involved two classes of instruments, MDCT and dental CBCT; the equipment are listed below:

- Vatec Picasso CBCT (E-WOO Technology Co., Ltd. (Factory No.2) 139-2, 138-2, Hagai-dong, Giheung-gi, Yongin-si, Gyeonggi-do Korea).
- iCAT Classic CBCT (Imaging Sciences International (ISI), Hatfield, PA, USA).
- KaVo 3D eXam CBCT (Imaging Sciences International (ISI), Hatfield, PA, USA).
- GE MDCT (General Electric Medical Systems, LightSpeed VFX Ultra, Tokyo, Japan).

The following materials were used in these *in vitro* studies, covered by the three Research Topics and resulted in four papers:

- ISI quality-assurance phantom;
- water phantom;
- mandible phantom with and without spine (specific developed);
- extracted upper premolar tooth of a mummy;
- cadaver heads or block of cadaver heads.

The study of the three Research Topics, which are itemised in details in the eight Thesis Points, resulted in four scientific publications as illustrated below.

Paper 1: This paper appeared as a book chapter. In this case, Picasso Pro dental CBCT equipment was used. The examined material was an extracted upper premolar tooth of a mummy. The reduction of X-ray scattering was due to the drastic reduction of the mass and size of material in the FOV, as the scan was taken only of this single tooth without the head. Thus, it was possible to arrive at a better image quality. This work has been based on an X-ray scattering study using iCAT Classic and KaVo 3D eXam equipment.

Paper 2: In this publication iCAT dental CBCT and GE MDCT instruments were utilized. To investigate the effect of the detector temperature and that of the calibration process of the flat panel detector (FPD) on the dental CBCT image quality, four different experimental conditions were used. Therefore these acquisitions were taken with and without warming-up period and calibration process of the FPD. Note that the MDCT measurements represent a *gold standard* in this field.

First, the measured grey values in Hounsfield units (HU) were compared for the four different experimental conditions of the four homogenous density materials of ISI quality-assurance CBCT phantom: air (1.29 kg/m^3=0.00129 g/cm^3), low-density polyethylene (LDPE) (0.92 g/cm^3), acryl (1.18 g/cm^3) and Teflon (2.16 g/cm^3). *Second*, for checking the spatial accuracy of the CBCT images in the four applied scan conditions, the visibility of the bar pattern at the centre of the ISI quality-assurance phantom was investigated.

Paper 3: The scientific basis of this paper was presented previously as two separate congress lectures, discussing the use of iCAT Classic CBCT equipment. The goal of the first congress lecture was to find a protocol and ideal contrast material concentration for the different mass size in the FOV using dental CBCT. The second congress lecture included the anatomical study of the intraosseous vascular territory (angiosomes) of the facial artery. In this examination, cadaver heads or block of cadaver heads were used. With an established procedure it was possible to minimize the presence of artefacts. For this reason a special calibration process was developed by varying different contrast material concentrations in order to achieve the maximal visibility of the contrast material filled vessels in soft tissues and bone. It was also necessary to create a special phantom to model both for the cadaver heads and the blocks instead of performing a real anatomical examination. For this preliminary study, contrast material filled plastic tubes were used in these phantoms during the dental CBCT acquisitions. The advantage of using these phantoms was the possibility to make several series of measurements using different concentrations of various types of contrast materials. On the basis of this preliminary study a predetermined concentration of the Microtrast contrast material solution (Microtrast, Guerbet GmbH, Sulzbach, Germany) was used in the anatomical study of filled vessels as outlined in **Paper 3**.

Paper 4: In this paper the same instruments were used as in **Paper 2**. The MDCT measurements represented the *gold standard* as in **Paper 2**. This *in vitro* study was performed using both an ISI quality-assurance phantom and a water phantom; the former of these was used in **Paper 2**. These experiments were performed using also the concept of sequential cone beam computed tomography (SCBCT), to obtain dental CBCT imaging with more realistic grey values (i.e. apparent density (AD)) and reduced noise. This yielded in lower standard deviation (SD) values, as compared with other scan modes using the same iCAT Classic dental CBCT. Dental CBCT technology using Feldkamp algorithm or its modifications, can lead to visualization of the high-contrast structure in the acquisition, similar to MDCT for the "bone window" range. Therefore those phantoms, which are containing lower-density materials inserts such as acryl or LDPE cannot be studied quantitatively using Feldkamp algorithm. In contrast to this, using the same dental CBCT equipment, all four inserts in this ISI quality assurance phantom will give more accurate grey value and lower SD value applying the SCBCT concept rather than Feldkamp algorithm. These experiments were designed to obtain a definite proof, that the SCBCT method gives better image quality. This point made it essential that the ISI quality-assurance phantom is used in this investigation presented in **Paper 4**.

4 Results and Discussion

The purpose of this dissertation was motivated by the *as-low-as-reasonably-achievable (ALARA) principle* which demands that the radiation dose for patients should be optimized to achieve the lowest practical level to address a specific clinical situation. For this reason, it is of considerable importance that we obtain the best necessary image quality at a certain radiation level. Thus, the purpose of this dissertation was the examination of grey values accuracy and improvement of image quality in dental CBCT at a given radiation level.

Thesis Points 1: It has been proven that in the case of a single tooth, it was possible to investigate the presence of dry soft tissue in a single tooth pulp chamber in the root canal. This was possible because there was no head around the investigated single tooth, consequently, the mass, and therefore the magnitude of X-ray scattering, in the FOV, was substantially reduced. This result is a clinical proof of previously published *in vitro* studies proving that the magnitude of noise in the reconstructed image depends on the mass and size of the material in the FOV.

Thesis Points 2: It was concluded that pre-processing methods are of significant importance. These include the warming-up period as well as the calibration process to reduce the noise in the reconstructed CBCT image to about a third of the full value.

Thesis Points 3: The noise can be minimized to about a third or a fourth of the total value by using the more accurate reconstruction algorithm (SCBCT), involving two separate rotations, with parallel central beams at 2 different fixed heights, during the image acquisition. Of course, the double exposure does not mean double dosage. For example, in the double exposure dental CBCT, instead of a 600 basic projection data set (600 RD), two 300 basic projection data sets are used, and therefore no extra exposure occurs.

Thesis Points 4: It was concluded that pre-processing methods are of significant importance. These include the warming-up period as well as the calibration process to optimise the function of the applied iCAT Classic flat panel detector and in order to reduce the presence of artifacts. Of the two processes the calibration process was more effective to achieve the aim of the thesis point then the warming-up period.

Thesis Points 5: It has been concluded that in the case of mapping of the angiosomes the calibration of contrast material concentration, is a highly effective method to reduce the presence of artefacts.

Thesis Points 6: It has been proven that in the case of a single tooth, it was possible to investigate the presence of dry soft tissue in a single tooth pulp chamber in the root canal. This was possible because there was no head around the investigated single tooth, consequently, the mass, and therefore the magnitude of X-ray scattering, in the FOV, was substantially reduced. The reduction of X-ray scattering eventually reduced the noise in the reconstructed image, as it has been concluded in **Thesis Point 1**. These changes also increased the contrast resolution and therefore yielded a better density response of the dental CBCT instrument.

Thesis Points 7: It was concluded, that the pre-processing methods, such as warming-up period and the calibration process, are of significant importance in improving the accuracy of grey values in the reconstructed dental CBCT image. The warming-up period is less important because it leads to only a 7.4% improvement, while the calibration process results in 13% accuracy increase. In contrast to these, both methods together yield only 15.7% improvement.

Thesis Points 8: It was concluded, that the application of a more accurate scanning and reconstruction algorithm, namely the double exposure overlap acquisition procedure involving sequential cone beam computed tomography (SCBCT), is of appreciable importance in improving the accuracy of grey values (i.e. apparent density) in the reconstructed dental CBCT image. The numerical improvements are the following:

- Teflon 27.8%
- LDPE 68.7%
- Water 82.0%
- Acryl 214.3%

It should be emphasized, that using iCAT Classic dental CBCT equipment, only the SCBCT algorithm gives positive grey values in the case of acryl. The 214.3% increase is due to the change from negative to positive of the grey value. This improvement has been achieved by using SCBCT instead of applying the Feldkamp algorithm or its modifications.

5 Conclusion

The various investigated methods aimed to improve the image quality at a given level of radiation. The most dramatic improvement in image quality, i.e. in grey value accuracy and lower level of noise, was obtained by satisfying the sequential cone beam computed tomography (SCBCT) requirements. In future developments a potentially promising step would be to program this method into new CBCT equipments and work together with software developers to fully achieve this potential.

6 Acknowledgments

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The author is grateful to VIP Dental Oral Radiology and Cone Beam CT Imaging Centres Ltd. for providing access to sophisticated X-ray imaging instruments.

7 References

7.1 Preliminary method oriented publications

Plachtovics M. Digital Volume Tomography: Cone beam CT imaging in dentistry, oral and maxillofacial surgery (original article in Hungarian: A Digitális Volumentomográfia: Cone Beam CT-k a fogászatban, az arc-, állcsont- és szájsebészetben.)
MRadiol 2009;83:254-262.

Plachtovics M. Practical advice on the application of cone beam CT imaging in implantology I. (original article in Hungarian: Gyakorlati tanácsok a digitális volumentomográfia implantológiai alkalmazásához I.)
Implantológia 2011;8:22-27.

Plachtovics M. Practical advice on the application of cone beam CT imaging in implantology II. (original article in Hungarian: Gyakorlati tanácsok a digitális volumentomográfia implantológiai alkalmazásához II.)
Implantológia 2012;9:30-38.

7.2 Publications directly related to the dissertation

Paper 1: **Plachtovics M**, Patonay L, Kerenyi T. What Pal Szechenyi's tooth tells us: Modern investigation of a tooth with digital volume tomography. In Lilla Alida Kristof and Vilmos Toth (ed.): In honour of Archbishop Pal Szechenyi. Contribution for the path of life and the results of the study of the mummy of Nagycenk. (Original chapter and book in Hungarian: Amiről Széchényi Pál foga mesél. Korszerű fogvizsgálat DVT-vel. In: Széchényi Pál érsek emlékezete. Adalékok az életúthoz és a nagycenki múmia vizsgálatának eredményei.) Universitas-Győr Nonprofit Kft., 2012. Győr, Hungary. ISBN 978-963-9819-95-5. pp. 136-141.

Paper 2: **Plachtovics M**, Goczán J, Nagy K. The effect of calibration and detector temperature on the reconstructed Cone Beam CT image quality. A study for the work-flow of the iCAT Classic equipment.
Oral Surg Oral Med Oral Pathol Oral Radiol. 2015;119:473-480. doi: 10.1016/j.oooo.2014.12.009. Epub 2014 Dec 31. **IF: 1.46**

Paper 3: Molnar G, **Plachtovics M**, Baksa G, Patonay L, Mommaerts MY. Intraosseous territory of the facial artery in the maxilla and anterior mandible: Implications for allotransplantation.
J Craniomaxillofac Surg. 2012;40:180-184. doi: 10.1016/j.jcms.2011.03.019. Epub 2011 Apr 1. **IF: 1.61**

Paper 4: **Plachtovics M**, Bujtar P, Nagy K, Mommaerts MY. High-quality image acquisition by double exposure overlap in cone beam computed tomography.
Oral Surg Oral Med Oral Pathol Oral Radiol. 2014;117:760-767. doi: 10.1016/j.oooo.2014.02.024. Epub 2014 Mar 13. **IF: 1.46**

Cumulative Impact Factor: 4.53

7.3 Additional publications

Pataky L, **Plachtovics M**. About Cone Beam CT Imaging (original article in Hungarian: A Cone Beam CT-ről.)
Dental Express 2006;9:3-6.

Plachtovics M. Of additional interest from the world of Cone Beam CT Imaging (original article in Hungarian: További érdekességek a 3D CBCT világából.)
Dental Hírek 2009;13:28-30.

7.4 Conference presentations related to the dissertation

Plachtovics M, Turak O, Osvay M: Examination of cone beam CT imaging by radiation dose measurements. Oral Presentation at the 17th International Congress of DentoMaxilloFacial Radiology, 2009, Amsterdam, Netherland

M Plachtovics, G Molnar, G Baksa, MY Mommaerts. The use of Digital Volume Tomography (Cone Beam CT) for mapping of the angiosome of the face. Oral Presentation at the Congress of the European Association for Cranio-Maxillo-Facial Surgery, 2010, Brugge, Belgium.

G Molnar, G Baksa, **M Plachtovics**, L Patonay, MY Mommaerts. Facial allotransplantation- Can the maxilla and mandibular symphysis survive on the facial artery? Oral Presentation at the Congress of the European Association for Cranio-Maxillo-Facial Surgery, 2010, Brugge, Belgium.

DECLARATION

I am glad to declare that Dr. Mark Plachtovics may use, in his Ph.D. Dissertation, our joint paper entitled:

Intraosseous territory of the facial artery in the maxilla and anterior mandible: Implications for allotransplantation*

published in **Journal of Cranio-Maxillo-Facial Surgery**

This anatomical study, which was published in the above paper, was to define the intraosseous vascular territory (angiosomes) of the facial artery. The question was whether it is possible, considering all the benefits, to use the so-called dental CBCT scan for the examination of this vascular system.
The following quotations are from published paper concerning the method used.

"*The artery was injected with a barium sulfate/xanthan gum suspension (Microtrast, Guerbet Gmbh, Sulzbach, Germany) in a gentle, pulsatilemanner. Two milliliters of Microtrast, diluted with 8 ml tap water, was used in each head.*"

"*Cone-beam computed tomography (CBCT) scans were taken with iCAT Classic (Imaging Sciences International, Hatfield, USA) from the 10 mandibular and maxillary segments. The slice thickness was 0.2 mm.*"

The above method for our joint paper was developed by Dr. Mark Plachtovics.

The aim of his method oriented study was to find a scanning protocol and contrast material concentration for dental CBCT to make a setup for 3D mapping of the angiosomes of the face. It was important for him to find the contrast material concentration range to differentiate the compact surface of the bone from the entering vessels through the nutritive foramina, but to reduce the artefacts. With his established procedure it was possible to minimize the presence of artefacts. For this reason, a special calibration process was developed by him varying different contrast material concentrations in order to achieve the maximal visibility of the contrast material filled vessels in soft tissues and bone. It was also necessary for him to create a special phantom to model both for the cadaver heads and the blocks instead of performing a real anatomical examination. For his preliminary study, contrast material filled plastic tubes were used in these phantoms during the dental CBCT acquisitions. The advantage of using these phantoms created the possibility to make several series of measurements using different concentrations of various types of contrast materials.
On the basis of his preliminary study a predetermined concentration of the Microtrast contrast material solution (Microtrast, Guerbet GmbH, Sulzbach, Germany) was used in the anatomical study of filled vessels.
All of these methods development work was carried out by Dr. Mark Plachtovics. Without the development such a method the above paper could not be publish. This paper appears as **Paper 3** in Thesis N° 5 in the dissertation of Dr. Mark Plachtovics.
I have not used and will not use in the future Dr. Plachtovics research work for any PhD dissertation which appeared in our joint paper as quoted above.

20 March 2015

Molnar
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* Molnar G, Plachtovics M, Baksa G, Patonay L, Mommaerts MY. Intraosseous territory of the facial artery in the maxilla and anterior mandible: Implications for allotransplantation. *J Craniomaxillofac Surg*. 2012;(40)180-184. DOI: 10.1016/j.jcms.2011.03.019.