Computed tomography to quantify tooth abrasion

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ABSTRACT

Cone-beam computed tomography, also termed digital volume tomography, has become a standard technique in dentistry, allowing for fast 3D jaw imaging including denture at moderate spatial resolution. More detailed X-ray images of restricted volumes for post-mortem studies in dental anthropology are obtained by means of micro computed tomography. The present study evaluates the impact of the pipe smoking wear on teeth morphology comparing the abraded tooth with its contra-lateral counterpart. A set of 60 teeth, loose or anchored in the jaw, from 12 dentitions have been analyzed. After the two contra-lateral teeth were scanned, one dataset has been mirrored before the two datasets were registered using affine and rigid registration algorithms. Rigid registration provides three translational and three rotational parameters to maximize the overlap of two rigid bodies. For the affine registration, three scaling factors are incorporated. Within the present investigation, affine and rigid registrations yield comparable values. The restriction to the six parameters of the rigid registration is not a limitation. The differences in size and shape between the tooth and its contra-lateral counterpart generally exhibit only a few percent in the non-abraded volume, validating that the contra-lateral tooth is a reasonable approximation to quantify, for example, the volume loss as the result of long-term clay pipe smoking. Therefore, this approach allows quantifying the impact of the pipe abrasion on the internal tooth morphology including root canal, dentin, and enamel volumes.

Keywords: Dental abrasion, rigid registration, affine registration, cone beam CT, micro CT

1. INTRODUCTION

Dental abrasion results from the physical wear affected by nails or pins, by oral hygienic procedures and especially by ancient clay pipes [1]. Twelve skeletons from former graveyards in Basel show ellipsoid-shaped abrasion marks, which are characteristic for extended pipe smoking. The chronic use of the clay pipe resulted in volume losses of the tooth hard tissues. Human teeth consist of a crown, which is visible in the mouth. This crown consists of dentin and enamel. Enamel, which surrounds the dentin, is the hardest tissue of the human body. The inner core of tooth contains the root canal with the nerves, blood and lymph system that supply the tooth. The dimension of pipe smoking wears can reach the pulp and cause infections and toothache [2].

One of the famous skeletons from Basel is termed 'Theo' as it was from the church St. Theodor in Basel. This skeleton is the basis of the multi-disciplinary project 'Theo, the pipe smoker – destiny of a Lesser Basel' with the aim to identify the unknown man deceased around 1800. This project tries to reconstruct the historical and socio-economical context of Theo's life using multi-disciplinary approaches [3]. The present communication aims to quantify the impact of the pipe smoking wear on the teeth, i.e. the volume loss and tissue alteration taking advantage of X-ray computed tomography and sophisticated three-dimensional data treatment. As the original shape of the damaged tooth is unknown, the mirrored contra-lateral tooth is hypothesized to be a reasonable approximation. To prove this hypothesis and to quantify the differences between the two teeth, 30 tooth pairs were included into the present study.

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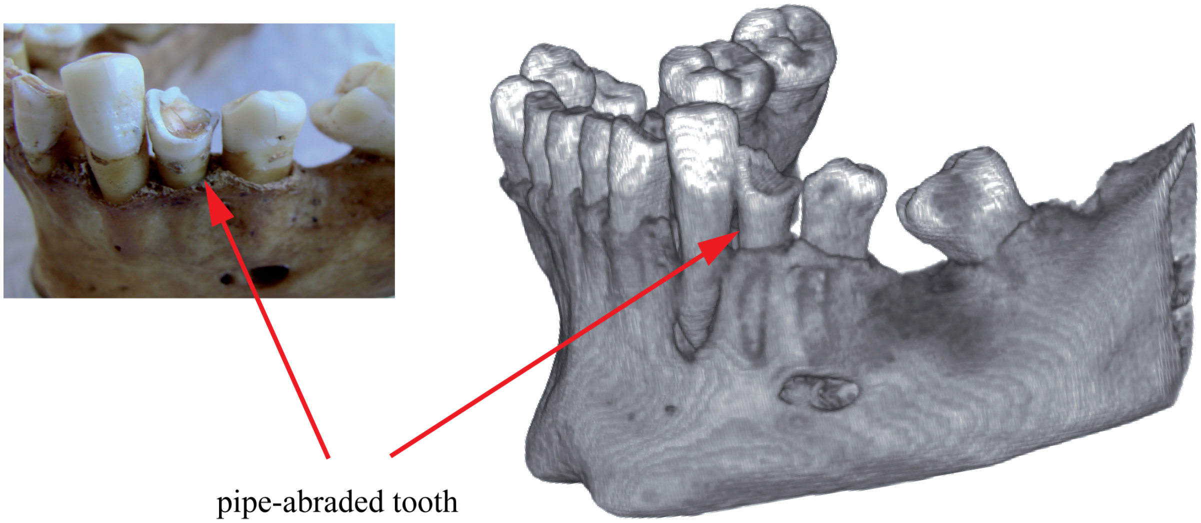

Figure 1. Habitual pipe-smoking forms dentition abrasions as represented by the photography and the 3D rendering of tomography data.

Characteristic dental abrasions, as visualized in Figure 1, had been described examining ancient skeletons in some detail. It has been known that the Basel clay pipes were imported at the second half of the 17th century from Holland and during the 18th century mostly from Germany. Within the 18th and the first half of the 19th century clay pipes became widely produced [4].

In 1984 in a rescue excavation near the St. Theodor's church in Basel the archaeological service unearthed 24 skeletons. Two of them showed in their teeth, similarly to the hospital cemetery skeletons, characteristic abrasion marks. One of the two, a man died in the age of 28 to 32 years is particularly interesting, because of the excellent state of preservation and the considerable abrasion marks. In the project a team of anthropologists, physicians, historians, and archaeologists tries to identify the unknown person 'Theo'. The graveyard was used only for a period of 53 years, namely from 1779 to 1833. During this period 4,334 people died in the parish of St. Theodor and were listed with their name, profession, and age at death in the parish record. With the help of different methods only 12 names have remained on the list of potential candidates. The team likes to prove Theo's origin by a DNA-analysis of the skeleton and the potential descendants. The project follows many approaches including stable isotopic analysis, face reconstruction and parish records/images to reconstruct Theo's personal life history and shed light on its socio-economic context [3]. The approach from dentistry analyzing the teeth by high-resolution, three-dimensional (3D) imaging should contribute to this multi-disciplinary initiative.

2. MATERIALS AND METHODS

2.1 Jaws of the Basel skeletons from the 19th century

Between 1984 and 1989 skeletons from the graveyard of the hospital and St. Theodor cemeteries were excavated by the archaeological service of Basel city. The hospital cemetery was used from 1845 to 1868 and the St. Theodor graveyard from 1779 to 1833 so that several thousand patients have been buried. In 1990 more than 80% of the excavated skeletons could be identified by the written records (register of deaths) and the anthropological data (sex, estimated age at death and pathologies) so that name, age at death, origin, profession and cause of death became uncovered. About 500 skeletons together with 330 transcribed medical records belonging to the skeletons have been stored in the Natural History Museum at Basel that is therefore a unique collection world-wide. These 500 skeletons contained twelve with characteristic abrasion marks. These dental abrasions cannot be related to chewing.

Most probably they result from the habitual smoking of clay pipes. Clay pipes consist almost entirely of aluminum silicate and sand. Holding the clay pipe habitually at the same position in the mouth generates one or more circular abrasions in the teeth [2,3] as visualized in Figure 1.

The final aim is the determination of the volume loss due to pipe smoking including an estimate of the related error bar. A set of 60 teeth, loose or anchored in the jaw, from 12 dentitions have been scanned and analyzed.

2.2 Cone-beam computed tomography

X-ray-based imaging techniques including cone beam computed tomography (CBCT) permit to visualize the three-dimensional structure of teeth and bone. Diseases and infections, which are often optically invisible, can be detected [5,6]. The power of CBCT is limited, since it is designed to image patients. The patient should only obtain a low X-ray dose so that the contrast is often insufficient for detailed quantitative analysis. Furthermore, streak artifacts from highly X-ray absorbing dental materials complicate the quantitative 3D analysis [7].

Because many of the teeth could not be extracted from the jaw, local tomography by means of the Accuitomo 60 and 80 (Morita, Kyoto, Japan) was performed with the aim to obtain 3D data of the teeth without damaging the alveolar bone of the skeleton. Before the data were recorded, two X-ray images in coronal and sagittal planes were taken to select the cylindrically shaped region of interest 60 or 80 mm high and 60 or 80 mm in diameter. The data acquisition implies the 360° rotation of X-ray source and detector around the specimen within a period of 18 s. The CCD-sensor acquired images with a pixel size of 0.16 mm × 0.25 mm. Based on these 512 projections, the supplier's software was used to reconstruct the 3D dataset. For the present study the accelerating voltage was set to 70 kV and the beam current to 4 mA. The data were converted into the DICOM format for further processing.

2.3 Conventional micro computed tomography

Micro computed tomography (μCT) systems are known to be efficient for quantitative bone and teeth evaluation, since the hard tissues exhibit reasonably high X-ray absorption contrast, see e.g. [8]. Therefore, several teeth were scanned by means of the SkyScan 1174™ system (SkyScan, Kontich, Belgium). The specimens fixed on the precision rotation stage were measured using an accelerating voltage of 50 kV and a beam current of 800 μA. Pixel size was adjusted between 20 and 28 μm depending on the size of the specimen. A series of 900 projections per tooth were acquired with an exposure time of 3.5 s per projection, resulting in a machine time of about 55 minutes per specimen As dentin and especially enamel are highly X-ray absorbing materials, a 0.5 mm-thick aluminum filter was used to harden the radiation. The data were reconstructed using the manufacturer's software (NRecon, Kontich, Belgium) and exported for further processing.

2.4 Synchrotron radiation-based micro computed tomography

Synchrotron radiation-based μCT (SRμCT) of one tooth was performed at the beamline W 2 (HASYLAB at DESY, Hamburg, Germany). This beamline including the tomography setup is operated by the GKSS Research Center [9]. A photon energy of 35 keV was chosen to acquire 720 projections in each of the 3 height levels. The total scan time corresponded to about 6 h. The projection pixel size corresponded to 4.6 μm and the spatial resolution, measured as the 10% value of the modulation transfer function (MTF) of a highly X-ray absorbing edge [10], was 8.8 μm.

2.5 Data processing

The software VG StudioMax 1.2.1 (Volume Graphics GmbH, Heidelberg, Germany) served for the segmentation of teeth from CBCT data after converting them from the DICOM to the TIFF-format. For the quantitative analysis, the abraded tooth and its undamaged contra-lateral counterpart were manually pre-registered.

The registration was automatically performed applying 3D rigid and affine registration algorithms with six and nine degrees of freedom, respectively [7,11,12]. By means of MATLAB code version 7.8 (MathWorks, Natick, USA) the volume loss due to abrasion was calculated.

As the original shape of the abraded tooth is unknown, we have chosen the contra-lateral tooth as the representative. Figure 2 illustrates the data treatment procedures. First, the abraded tooth of interest was mirrored to become self-similar to its contra-lateral counterpart. Second, based on rigid and affine registration algorithms, the abraded tooth was registered with its contra-lateral counterpart. The applied algorithms provide six parameters (three translational and three rotational degrees of freedom) for rigid registration and nine parameters (three additional scaling coefficients in the three orthogonal directions) for the affine registration. Third, in order to determine the loss of tooth hard tissues, the main component of the difference, given by the green color in Figure 2, was identified.

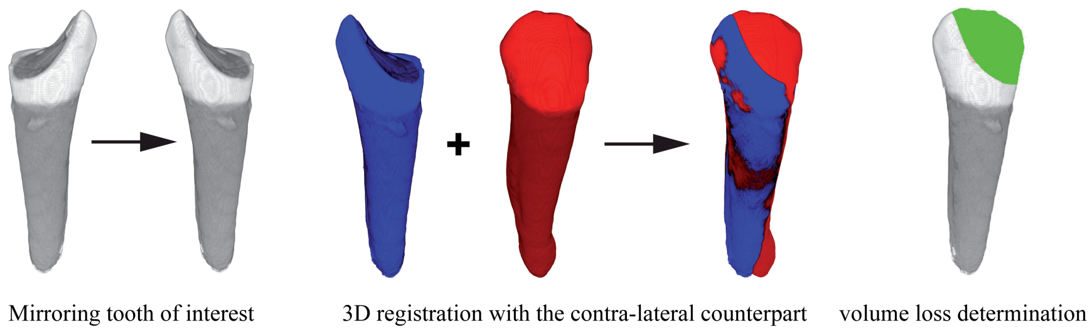

Figure 2. Procedure of the 3D registration of the pipe-abraded tooth and its contra-lateral counterpart for the quantification of the volume loss: the green color represents the volume of interest.

3. RESULTS

3.1 Comparison between the X-ray tomography modalities

Figure 3 shows a 3D rendering of CBCT data from the jaw together with a 3D rendering of the abraded tooth and two selected slices for each of the utilized acquisition methods, i.e. CBCT, µCT, SRµCT. The slices, perpendicular to each another, show in qualitative manner, how the spatial resolution improves from CBCT via conventional µCT to SRµCT. The edges of the tooth, the root canal wall and the interface between dentin and enamel appear blurred in the CBCT data, while they appear sharper in the µCT data. The overall shape of the tooth, however, can be clearly identified in the CBCT data, and the differently absorbing tooth hard tissues dentin and enamel can be distinguished. The improved spatial resolution is seen best at the crack through the tooth center. Here, the pixel size is essential to quantify the morphology and extension of the crack.

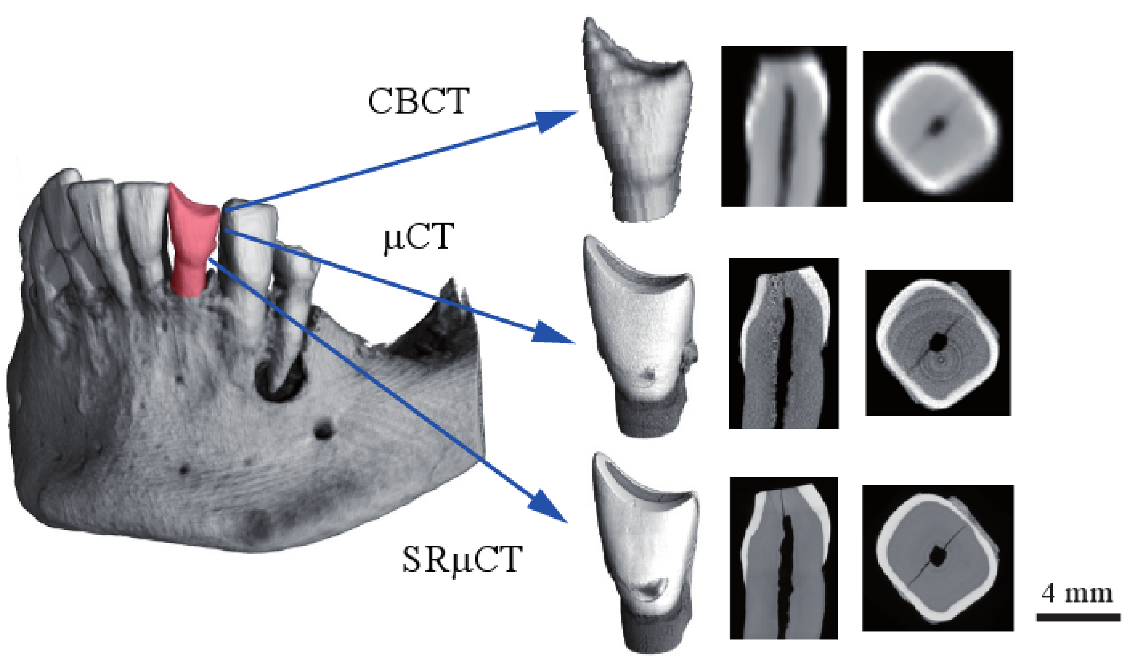

Figure 3. 3D rendering of the jaw generated from CBCT data, where the tooth of interest is red colored. The 3D representations of this tooth together with two selected slices perpendicular to each another qualitatively show the power of the X-ray tomography techniques applied: CBCT, conventional µCT, and SRµCT.

In order to demonstrate the resolution power of the three tomography-techniques for the abraded tooth, the histograms are shown in Figure 4. The left peaks in the graphs near zero correspond to the air. The main peaks in the center of the diagrams are related to dentin as indicated. The dentin has a much larger volume than the enamel that corresponds to the peak in the right part of the diagrams. The μCT data allow for clear discrimination between dentin and enamel, whereas the enamel almost disappears in the noise of the CBCT histogram. The voxel lengths in μCT are generally a factor 5 to 10 smaller than those of CBCT and consequently exhibit much less blur at the interfaces (air-enamel, enamel-dentin, dentin-air). The sharpness of the peaks relates to the number of photons applied for the imaging.

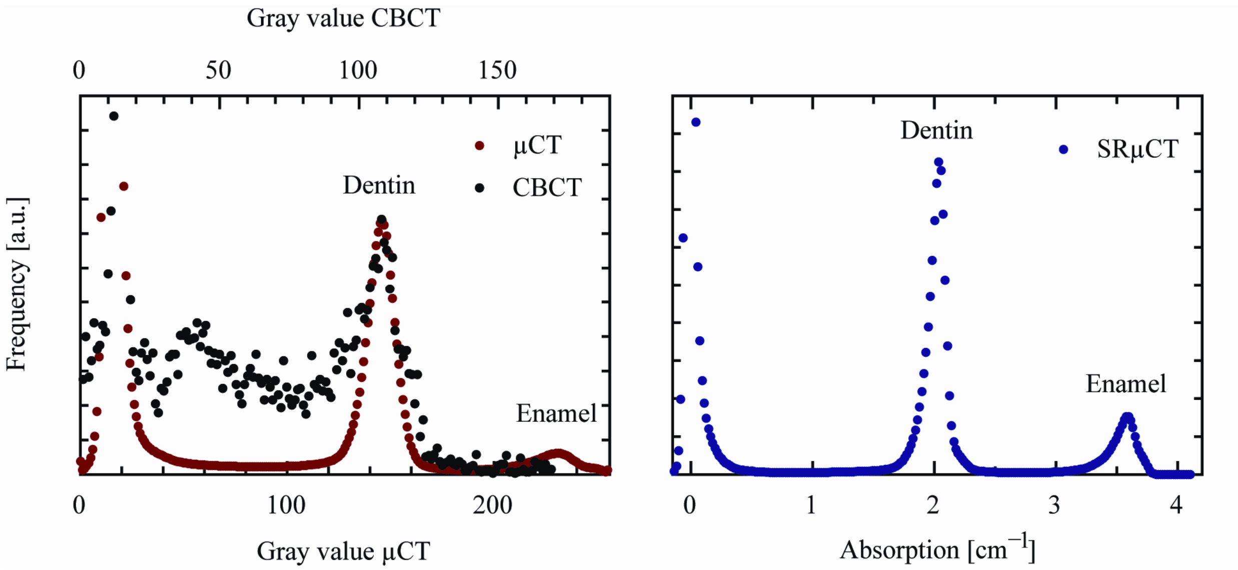

Figure 4. Histograms of CBCT and μCT as well as SRμCT of the selected tooth, cp. Figure 3. One can clearly identify the dentin. The enamel peak is only well separated for the μCT techniques.

3.2 Comparison of teeth with their contra-lateral counterparts

As the teeth on the right and the left in the human mandible slightly differ in shape and size, one should quantify these differences to estimate the expected error bars for the quantification of the hard tissues losses as the result of extensive clay pipe smoking. Table 1 shows the scaling factors obtained from the affine registration of 30 tooth pairs in the occlusal-apical, buccal-oral and mesial-distal directions. The mean scaling factors, also given in Table 1, are comparable for the three directions and well below 4%.

Table 1. The three scaling factors for affine registration of 30 tooth pairs. The description in the first column contains the identification of the skeleton and the two teeth compared.

Left-right comparison	**Occlusal-apical [%]**	**Buccal-oral [%]**	**Mesial-distal [%]**
431_13_23	7.93	0.15	5.22
431_33_43	8.35	2.07	0.21
462_13_23	3.46	0.74	4.66
462_32_42	4.00	0.07	0.46
462_43_33	11.00	16.62	16.17
545_32_42	10.97	7.01	7.20
562_33_43	0.00	2.23	2.16
600_14_24	2.28	2.30	5.53
655_13_23	7.29	3.86	6.55
655_32_42	0.79	0.27	3.70
655_33_43	0.31	0.36	0.59
931_13_23	2.80	1.95	0.58
931_33_43	2.84	1.63	1.06

1650_12_22	1.29	0.52	0.21
1650_13_23	0.81	1.93	0.63
1806_13_23	0.05	4.10	3.03
1806_14_24	1.57	1.43	5.45
1806_34_44	3.98	2.00	1.98
1900_32_42	0.30	2.28	0.67
1900_34_44	11.88	11.87	9.12
FK15375_32_42	1.00	0.00	0.00
FK15375_34_44	0.49	1.56	0.86
FK15375_33_43	3.00	7.00	0.57
Theo_11_21	2.57	2.82	1.41
Theo_12_22	6.41	0.86	1.78
Theo_14_24	0.49	0.51	0.57
Theo_15_25	0.07	7.92	6.05
Theo_32_42	2.00	4.80	0.80
Theo_34_44	5.00	3.85	0.35
Theo_35_45	7.94	7.09	9.27
Mean scaling factor	**3.70**	**3.33**	**3.23**
Standard deviation	3.56	3.72	3.65

3.3 Determination of the apical volume loss of abraded teeth

Tables 2 to 4 list the apical volume loss calculated by means of rigid and affine registration algorithms for incisor, canine and premolar pairs. For the incisor and canine pairs the weighted mean values derived by means of affine registration are significantly larger than the values found by the rigid registration. The weighting reduces the magnitude of the mean values significantly; un-weighted values are 12.6 and 15.8 mm^3 for the incisors (affine and rigid registration, respectively), 13.6 and 20.4 mm^3 for the canines and 19.9 and 27.9 mm^3 for the premolars. The error bars calculated from weighted standard deviations are larger for the rigid registration compared to the affine one.

Typical values for the wear-induced volume loss correspond to a few percent of the hard tissues of the entire tooth. Values larger than 10% are the exception. Volume losses above 21% were not noticed.

Table 2. Apical volume loss for incisor pairs determined using affine and rigid registration algorithms.

	Affine registration		**Rigid registration**	
Incisor pairs	Volume loss [mm^3]	Volume loss [%]	Volume loss [mm^3]	Volume loss [%]
462_32_42	22 ± 1	5.9	27 ± 3	7.4
545_32_42	3 ± 1	0.8	3 ± 6	0.8
655_32_42	3 ± 4	0.8	5 ± 3	1.3
1650_12_22	1 ± 1	0.3	2 ± 1	0.6
1900_32_42	60 ± 8	16.9	62 ± 10	17.2
FK15375_32_42	3 ± 1	0.8	3 ± 1	0.8
Theo_11_21	3 ± 3	0.6	12 ± 5	2.2
Theo_12_22	6 ± 4	1.8	12 ± 7	3.8
Weighted mean	**7.2 ± 1.2**		**4.3 ± 1.5**	

Table 3. Apical volume loss for canine pairs determined using affine and rigid registration algorithms.

	Affine registration		Rigid registration	
Canine pairs	Volume loss [mm^3]	Volume loss [%]	Volume loss [mm^3]	Volume loss [%]
431_13_23	23 ± 5	2.4	13 ± 31	1.6
431_33_43	3 ± 5	0.5	10 ± 15	1.6
462_13_23	9 ± 4	0.9	28 ± 16	3.4
462_43_33	7 ± 1	0.6	25 ± 33	2.3
562_33_43	10 ± 1	3.3	11 ± 4	3.6
655_13_23	14 ± 20	1.6	43 ± 53	5
655_33_43	6 ± 3	0.8	8 ± 1	1
931_13_23	27 ± 1	3.3	33 ± 7	4.3
931_33_43	34 ± 8	4.5	53 ± 21	8.7
1650_13_23	11 ± 8	1.7	14 ± 7	2.2
1806_13_23	15 ± 3	3.2	4 ± 6	0.8
FK15375_33_43	4 ± 2	0.7	3 ± 2	0.5
Weighted mean	**13.6 ± 1.5**		**7.8 ± 1.8**	

Table 4. Apical volume loss for premolar pairs determined using affine and rigid registration algorithms.

	Affine registration		Rigid registration	
Premolar pairs	Volume loss [mm^3]	Volume loss [%]	Volume loss [mm^3]	Volume loss [%]
600_14_24	10 ± 4	2.0	18 ± 7	3.7
1806_14_24	23 ± 23	5.1	25 ± 19	5.6
1806_34_44	12 ± 23	2.7	10 ± 2	2.3
1900_34_44	7 ± 16	1.4	63 ± 110	12.3
FK15375_34_44	7 ± 1	0.9	3 ± 4	0.4
Theo_14_24	12 ± 25	2.0	9 ± 21	1.6
Theo_15_25	27 ± 16	5.6	51 ± 39	12.5
Theo_34_44	76 ± 5	20.4	69 ± 25	20.3
Theo_35_45	5 ± 3	1.0	3 ± 7	0.6
Weighted mean	**9.3 ± 1.7**		**9.3 ± 3.4**	

4. DISCUSSION

4.1 Choice of X-ray tomography setup

The datasets for the quantitative comparison of tooth pairs for the determination of volume loss due to pipe smoking were generated using CBCT, conventional µCT and SRµCT. The methods differ with respect to density and spatial resolution, data size, acquisition time and radiation dose.

CBCT, widely used in dento-maxillofacial radiology, is based on a conventional X-ray tube. Therefore, exposure times of about 20 s lead to a radiation dose tolerable for patients. The volumetric CBCT data allow visually distinguishing between the individual hard tissues (enamel, dentin, bone) and soft tissues or air. Thus the technique is widely used for implant placement planning [5,6].

Since CBCT permits to perform measurements of the entire mandible and to acquire data of a cylinder 8 cm in diameter and 8 cm high (local tomography), it is suited to visualize teeth, which cannot be removed from the dentitions without significant damages of the alveolar bone. The historical skeletons are of high value, and alveolar bone damages are not tolerable.

Sometimes, the teeth can be extracted from the jaw without any problem. The extracted teeth have a diameter well suited for μCT techniques. The much better spatial resolution and contrast of μCT in comparison to CBCT is the result of acquisition times that correspond to hours due to increased photon statistics and smaller detector pixel sizes. Since dose is not a crucial issue for dental anthropology, μCT has developed to a powerful imaging technique of unique human and animal teeth, see for example [13].

The unique specimens in anthropology are often recorded at the synchrotron radiation sources [13-15]. Because of the improved photon statistics [9] and the monochromatic X-ray beam, SRμCT yields quantitative data on local X-ray absorption not achievable by the currently available conventional, laboratory-based tomography systems [12]. The conventional μCT systems, however, have reached a level that quantitative bone analysis (morphometry) became possible [16]. Therefore, we have hypothesized that wear-induced enamel and dentin losses can be quantitatively evaluated using conventional μCT scanners such as the SkyScan 1174™ system. The availability of the laboratory-based systems allows for extended studies so that a series of several tens of teeth could be included into the present publication. The results elucidate that the conventional μCT data are precise enough to extract quantitative values of tooth shape in general and tooth abrasion in detail.

A histogram analysis of the data from teeth is reasonable. Besides the peak that originates from air, one finds well-separated peaks from the dentin and the stronger X-ray absorbing enamel. Even the SRμCT data of enamel and dentin do not perfectly exhibit the Gaussian shape [17] indicating the hard tissue inhomogeneities. The area below the peaks, however, yields the volume of the different components in an easy way. Hence, the size of the tooth of interest and its enamel-dentin ratio are available. The interface area can be derived from the analysis of the partial volume.

Although we regard the conventional μCT as the method of choice for the present study, CBCT and SRμCT yield complementary information and should be included for future experiments and data analyses.

4.2 Similarities of contra-lateral teeth

Orthodontic studies are available, which compare the intra- and inter-arch tooth size and shape. For example some decades ago [18], the correlation of the left and right mesio-distal crown diameters was measured. So far, however, the detailed comparison of contra-lateral teeth based on 3D registration, which delivers quantitative data on the similarities in the occlusal-apical, mesial-distal and buccal-lingual directions, is missing.

The affine registration shows that the differences in shape and size between the tooth of interest and its contra-lateral counterpart are generally only a few percent, indicating the high degree of similarity in shape and size between left and right side of the jaw. Asymmetric dental sizes and scaling factors above 10% suggest dental abnormalities, malformation and syndromes providing a malocclusion [19,20]. Therefore, the contra-lateral tooth is an acceptable model to evaluate the volume loss due to the pipe abrasion.

Perfect mirror symmetry of the teeth from the left and the right part of the mandible, however, is only accidentally given, as seen from the values in Table 1. Therefore, individual deviations from this symmetry have to be considered. The deviations, however, seem to be generally rather small as the incorporation of the scaling parameters, that means a change from rigid to affine registration results in only a moderate reduction of the error bar. Therefore, one can conclude that the rigid registration is already a good estimate for the quantification of tooth abrasion.

4.3 Tooth abrasion owing to chronic clay pipe smoking

The chronic clay pipe smoking induces the significant loss of enamel and dentin. The amount of hard tissue loss depends on many factors. It has been crucial how the clay pipe was used. The aluminum silicate and sand of which the clay pipe mouthpieces consist are harder than the enamel and much harder than the dentin. Hence, one may restrict to the enamel that dominates the abrasion rate. Clay pipes were light-weight and could be hold in the mouth more or less at the same spot for extended periods of time [21] leading to the observed dental abrasion.

Compared the total tooth volume, the loss of enamel and dentin with a value well below 10% is indeed small. One has to consider, however, that the crown is only about 1/3 of the tooth, as the larger part is anchored in the alveolar bone and not exposed to the action of clay pipe smoking. The percentage would reach much larger values, when just the enamel is considered.

The energy to clench the pipe stem between the teeth was relatively small. The mouthpieces were often glazed and coated in wax to reduce the surface roughness. Therefore, the dental abrasion is not only a function of the human tissues but also a function of the pipe. The minor volume loss could also be attributed to the fact that clay pipes were used as a whistle or counter, leading to a reduced use [22].

Only two specimens (1900_32_42 and Theo_34_44) showed a severe volume loss above 10%. Especially among laborers, heavier and thicker pipes were popular. They often needed both hands to work and held the clay pipe between the teeth, resulting in a higher abrasion rate [21]. The severe loss of substance could be also a result of a period of malnutrition during the development of the permanent tooth [3]. Malnutrition has the effect that the dental hard tissue is less mineralized and susceptible for higher abrasion due the clay pipe smoking.

The inter-individual difference of volume loss results in most of the cases because the pipe smokers held the clay pipe with two teeth, normally one with a high and the other one low abraded loss of volume. In some of the pipe smokers' dentitions more than one circular pipe abrasions can be detected. Both factors have to be considered when the mean volume loss is considered.

The weighted mean calculated volume loss after affine registration was highest in the canines, which might be explained by the position stability of the pipe within the mouth.

4.4 Impact on dental medicine

In orthodontics, the diagnosis and the treatment of malocclusion require an accurate knowledge of the tooth morphologies. The correct analysis of the denture's geometry is essential to achieve optimized occlusal-apical, mesial-distal and functional buccal-lingual occlusions. Because the similarity is given in most cases, the contra-lateral teeth often assist the reconstruction of carious lesions or larger damages during dental treatments, where the original morphology is unknown, and a functional and esthetic result is highly desirable. The aim to copy the nature is an important factor in aesthetic dentistry. Even in orthodontics, the treatment of malocclusion requires an accurate knowledge of the tooth dimension to achieve an ideal and functional occlusion [19].

The procedure developed allows studying the similarities and differences between the teeth from the left and right parts of the upper and lower jaws in quantitative manner.

5. CONCLUSION

For the extracted teeth, conventional μCT can be regarded as the method of choice for the determination of the tooth abrasion from extensive use of clay pipes, as it delivers reasonably precise results with limited affords.

The mirror symmetry between tooth of interest and contra-lateral counterpart is given within a very few percent. Therefore, the contra-lateral counterpart is a suitable reference for the determination of tooth abrasion from extensive use of clay pipes and the current dental treatments.

3D registration algorithms allow calculating tooth hard tissue volume loss for example caused by chronic clay pipe smoking. The smaller error bars obtained with the affine registration indicate the more precise analysis of affine registration compared to the rigid one. Nevertheless, results obtained with the rigid registration algorithms are within a reasonable range.

High-resolution tomography studies of human teeth post mortem combined with sophisticated software tools yield innovative insights into anthropology and current approaches to dental treatments.

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