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TECHNICAL REPORT

Virtual radiographs computed from TACT® volume data as a gold standard for image registration prior to subtraction

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Objective: To develop a three-dimensional (3D) model for quantitative analysis of image subtraction methods simulating clinical conditions and relevant to dental radiology.
Method: A high-resolution volume representation of a formalin-preserved segment of a human maxilla was synthesized from a set of 51 digital radiographs equidistantly covering the entire sampling aperture by means of Tuned-Aperture Computed Tomography® (TACT®). Two-dimensional (2D) projection renderings of a 3D model were generated yielding arbitrary but well-known 2D projections with, and without, structured noise producing 'virtual radiographs'.
Results: Virtual radiographs were found to be similar to actual clinical images with respect to appearance, structure, and texture. Because the TACT reconstruction process allows all possible positions and orientations of source, specimen, and image plane to be simulated with negligible under sampling over a reasonable range of solid angles (sampling aperture), the resulting 3D model provided a rigorous method for establishing a truly objective gold standard (ground truth) for testing different registration techniques.
Conclusions: TACT image registration can be assessed quantitatively by comparing actually observed *vs* theoretically professed parameters that presumably constrain the underlying projection geometries. Other attributes that vary from one method to the next, such as the use of nonlinear or region-specific techniques to facilitate registration, likewise, now can be rigorously measured by context-based methods such as quantitative determination of image similarity. Hence, a 3D model that renders idealized virtual radiographs from any desired projection geometry makes possible truly objective comparison of various digital subtraction techniques.
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Introduction

The detection of small changes in serial radiographs has been achieved using subtraction for more than 20 years. The process requires that standardized radiographic films be digitized, registered with respect to geometry as well as contrast, and subtracted, where both the projection geometry and the film processing need sufficient standardization. Meanwhile, solid-state sensors or storage phosphor plates directly provide digital serial radiographs. In addition, third-generation systems for subtraction perform *a posteriori* registration of geometry and contrast through the application of suitable computer algorithms. Nonetheless, automatic subtraction is still not used in routine diagnosis and patient treatment. This is partly caused by the incomparability of the various algorithms for image registration prior to subtraction.[1]

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Results of computerized *a posteriori* registration have been demonstrated on numerous occasions using *in vivo*, *in vitro*, or phantom images in combination with miscellaneous artificial manipulations.[2] On the one hand, an evaluation based on real data is necessarily obtained with uncontrolled geometry and, therefore, lacks the required ground truth (gold standard). On the other hand, an evaluation based on simulations within plain radiographs is less meaningful for clinical use because most problems involving computer-based registration arise from differences in X-ray projection geometry that cause modifications in image content, which cannot be simulated accurately from two-dimensional projections.

More generally, a robust gold standard must fulfill three criteria:[3] (1) it should be established by a method that itself is precise, i.e. reproducible; (2) it should reflect the patho-anatomical appearance of the disease; and (3) it should be established independently of the diagnostic method under evaluation.

With respect to image registration prior to subtraction, Criterion 2 means that changes in image content resulting from beam alterations (i.e., structured noise) must be inherent to the gold standard. Furthermore, artificial manipulations which are based on a single plain radiograph clearly validate Criterion 3. Nevertheless, simulations that are based on several images might become suitable for the evaluation of registration procedures, if the source data is obtained from other modalities, such as computed tomography (CT). In any case, some sort of a three-dimensional (3D) model is required to obtain complete independence between the registration process to be evaluated and the associated geometry assumed to be constraining the resulting projections.

Although CT provides a 3D representation of the object's attenuation coefficients and enables the computation of virtual radiographs in any imaging geometry, modern spiral CT devices still provide insufficient spatial resolution for realistic virtual intra-oral imaging. Hence, they are restricted for preparatory training in dental radiographic imaging techniques.[4]

Figure 1 Embalmed lateral anterior maxillary tissue segment

Lötjönen *et al*. compute virtual X-ray projections from magnetic resonance imaging (MRI).[5] The MRI volume is segmented into thorax and lungs, and both classes of tissue are labeled with constant attenuation coefficients. Hence, their results are of poor quality and also not suitable for evaluation of registration algorithms, i.e., they violate Criterion 2.

Accordingly, this research aims to establish a gold standard for geometric registration, i.e., a reliable method (Criterion 1) of producing realistic radiographs with *a priori* known ground truth for registration (Criterion 2), by means of Tuned-Aperture Computed Tomography® (TACT®) (Criterion 3). In contrast to other 3D imaging modalities, the spatial x,y-resolution of a TACT volume is similar to that of the direct digital imaging device used for data acquisition, while the resolution in the z-direction is controlled by the size of aperture and the number of projections acquired for TACT reconstruction.[6]

Materials and methods

Generation of the volume representation

A high-resolution TACT volume representation was produced using projection data obtained from a formalin-preserved lateral anterior maxillary segment of approximately 1 cm thickness (Figure 1). The segment was attached directly to a dental charge-coupled device (CCD) sensor (Schick Technologies, Long Island City, NY, USA) with radiolucent tape, and subsequently radiographed in a systematic fashion using a conventional intra-oral X-ray tube head (Siemens Heliodent, Siemens Medical Systems, Iselin, NJ, USA) operating at 60 kVp with 1.5 mm total aluminum equivalent filtration. Two tiny steel ball bearings were attached in arbitrary positions to the facial surface of the specimen to serve as fiducial markers required for TACT reconstruction. Each had a nominal diameter of 0.5 mm. The projection angles were systematically varied by moving the specimen (with attached sensor) in a plane parallel to the CCD array while keeping the tube head in a fixed position above this plane (Figure 2). This expedient resulted in a constant orthogonal projection distance of 30 cm producing a uniformly sampled projection 'aperture' characterized by a solid angle of approximately 35 degrees. The latter was

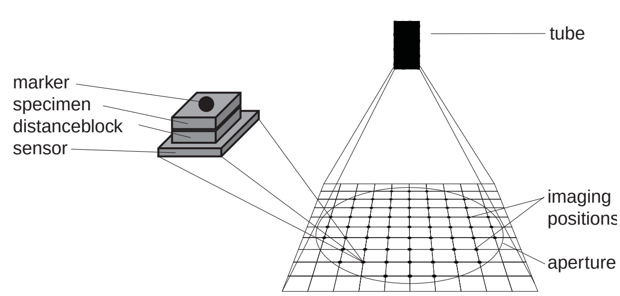

Figure 2 Experimental setup for raw data acquisition

determined by the collimated diameter of the primary beam at the fixed focal-object distance. A total of 51 uniformly spaced projection radiographs were retained after eliminating all projections exhibiting cone cuts. A total of 202 TACT slices encompassing the entire thickness of the specimen were synthesized. The spatial resolution of the resulting simulation model was $524 \times 760 \times 202$ voxels scaled to a virtual volume measuring approximately $26 \times 38 \times 10$ mm (Figure 3). Of course, any other desired specimen or clinical phantom could have been used in place of the maxillary segment selected for this demonstration.

Model of X-ray projection

Assuming a point-shaped focal spot and fixed coupling between the X-ray tube and the irradiated object, it has been shown[7] that the model of perspective projection exactly describes changes in pixel co-ordinates that result from any movement of the sensor plane in space (six degrees of freedom; three degrees of rotation and three degrees of translation). In other words, a subtraction image that is based on serial radiographs conforming to these projective restrictions and characterized by ideal *a posteriori* registration would only contain unstructured or random noise. Contrarily, structured noise is obtained from diagnostically irrelevant background structures resulting from misalignments in subtraction.[8]

In free-hand radiography, tube and patient are uncoupled. With respect to linear dependencies within the resulting system of equations, the 18 degrees of freedom (three degrees each of rotation and translation for the tube, the object, and the sensor) reduce to eight including all six degrees of sensor movement.[7] Nevertheless, image content is changed by the modified projection paths traversed by the X-rays. Hence, structured noise is obtained for registered free-hand radiographs even if imaging geometry of the baseline is carefully restored for acquisition of the follow-up projection. According to Criterion 2, this effect must be taken into account by a robust gold standard.

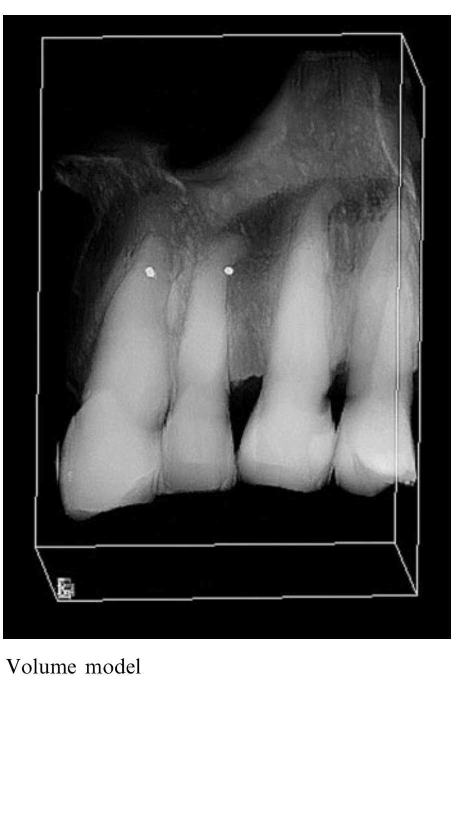

Figure 3 Volume model

Computation of virtual radiographs

Virtual radiographs were obtained from volume renderings. The virtual tube was placed at a clinically representative focal-object distance of $d+150$ mm, where $d=0$ denotes the initial setting. Virtual X-ray beams were emanated toward the virtual maxilla, which is represented by voxels of certain attenuation according to the TACT volume representation. Every ray traverses a large number of voxels in the maxilla model.[9] A virtual digital sensor was placed about 10 mm behind the virtual maxilla (Figure 4). The virtual radiographs were generated by a nonlinear reconstruction method and a maximum-brightness ray-tracing rendering.[10] In addition to this general setup, the following parameters were varied: (1) the focus–object distance $d+150$ mm was altered as indicated by a changed value for distance d; (2) the horizontal angulation of the tube α was altered relative to its normal position; and (3) the virtual sensor plate was moved and rotated arbitrarily around its normal position. The resulting change in image co-ordinates is described below as defined by a perspective projection

$$x' = \frac{a_1 x + a_2 y + a_3}{a_7 x + a_8 y + 1}, \quad y' = \frac{a_4 x + a_5 y + a_6}{a_7 x + a_8 y + 1} \tag{1}$$

where (x,y) and (x',y') denote the pixel co-ordinates in the sensor plane before and after the alteration, respectively, and the eight parameters $a_i \in \mathrm{IR}$ determine the perspective projection.

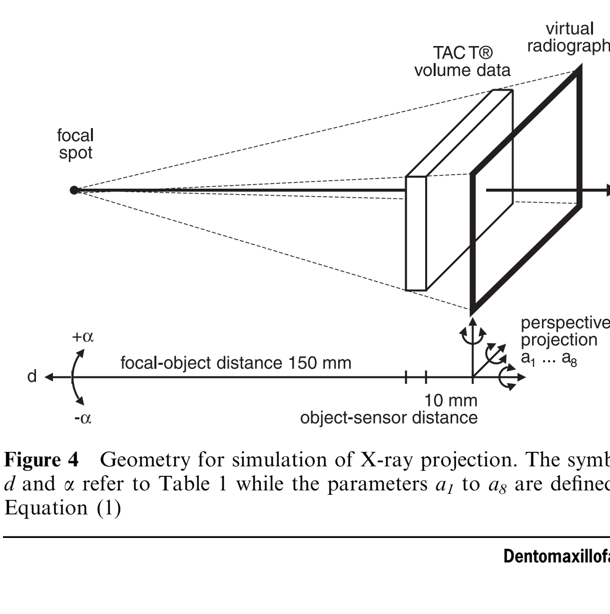

Figure 4 Geometry for simulation of X-ray projection. The symbols d and α refer to Table 1 while the parameters a_1 to a_8 are defined in Equation (1)

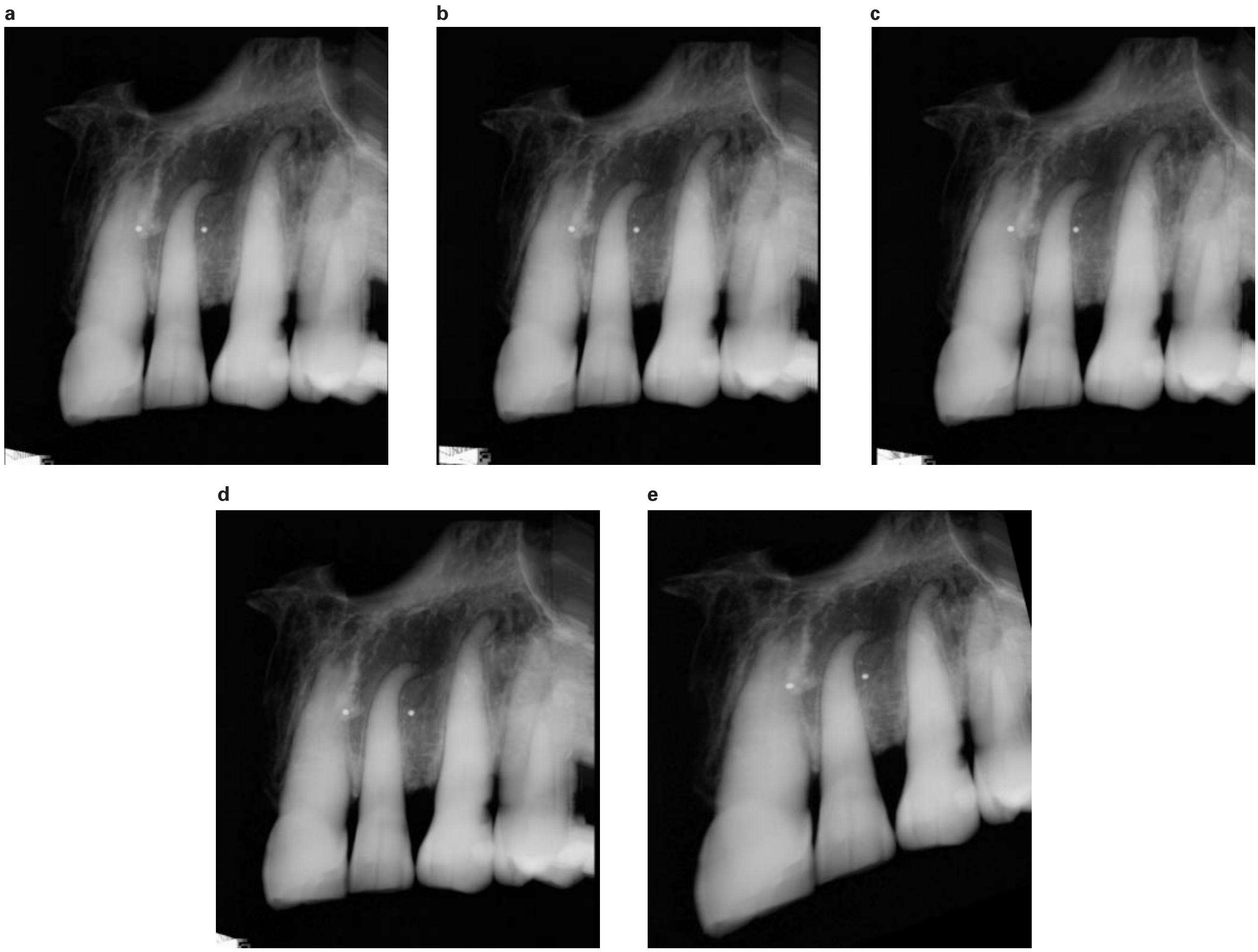

Figure 5 Virtual radiographs based on TACT. The preset geometry used for computation of the images is summarized in Table 1

Table 1 Settings for computing the virtual radiographs in Figure 5

Panel	d	α	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
(a)	0	0	1	0	0	0	1	0	0	0
(b)	100	0	1	0	0	0	1	0	0	0
(c)	0	+5	1	0	0	0	1	0	0	0
(d)	0	−5	1	0	0	0	1	0	0	0
(e)	0	0	1.36	0.03	−82	−0.01	0.92	−12	0.0005	−0.0003

As defined in Figure 4, d and α determine the additional focal-object distance and the horizontal angle between the tube and the object's main axis, respectively. The parameters a_1 to a_8 determine the perspective projection (Equation 1) which is obtained by free movement of the sensor plane

Results

Figure 5 shows an ensemble of virtual radiographs. The artifacts on the right side of the image result from the limited field of view of the CCD sensor that was used for the initial generation of projection radiographs, on which the TACT volume representation is based. Starting from the baseline (a), the focal–object distance was enlarged (b), the tube was rotated horizontally (c) and (d), and the position of the sensor plane was modified (e). The corresponding parameters are listed in Table 1. All of the virtual radiographs look quite realistic and are representative of what one would expect to obtain clinically. However, because any geometry of source, volume, and sensor can be selected to compute virtual radiographs, the great variety of resulting images could not be summarized in only one figure.

Movements of the X-ray source induce structured noise when images are registered with respect to perspective projection. This is exemplified in Figure 6. The subtraction of the virtual radiographs (Figure 5a,b) shows structured noise resulting from alterations of the X-ray beam path. Hence, TACT-based virtual radiographs satisfy Criterion 2 for robust gold standards.

Figure 7 summarizes a typical system for evaluation of the performance of registration by means of virtual radiographs. After the selection of any object and acquisition of the source data, the high-resolution

Figure 6 The subtraction of virtual radiographs (Figure 5a,b) has been contrast enhanced to demonstrate structured noise resulting from alterations of the X-ray beam paths

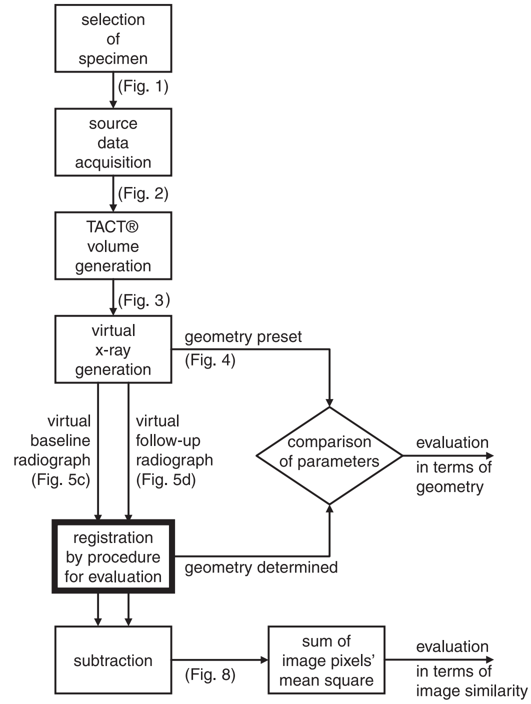

Figure 7 Flowchart for the performance evaluation of registration procedures by means of virtual radiographs computed from high-resolution TACT volume data

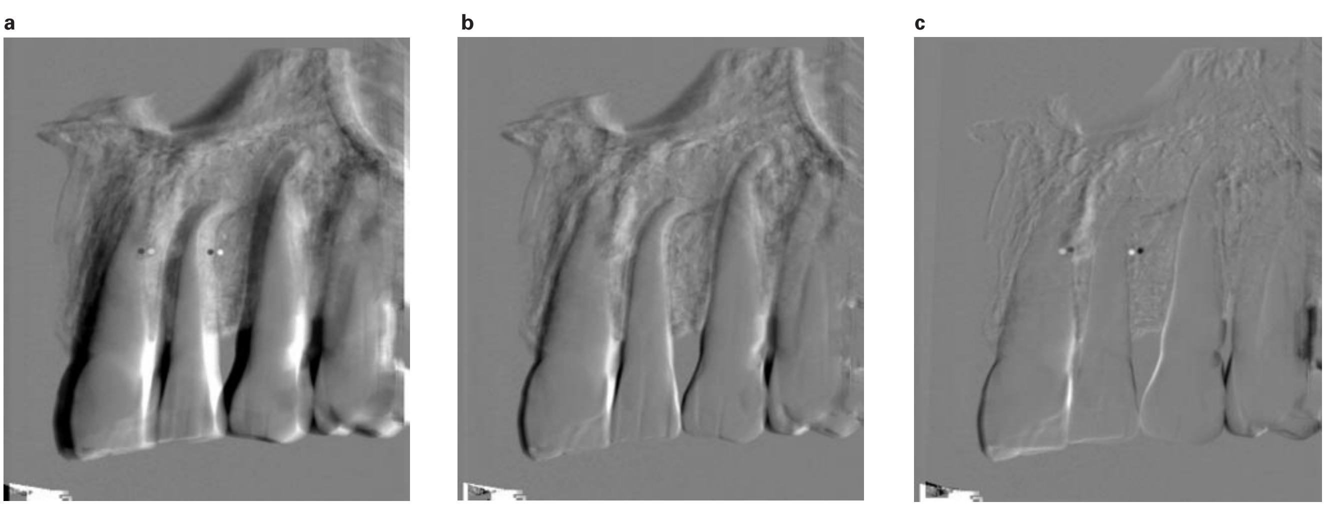

Figure 8 Representative subtraction images obtained from Figure 5c,d after (a) no correction, (b) affine correction (rotation, scale change, translation) and (c) projective correction (perspective)

TACT volume is generated. A pair of virtual X-rays is computed and passed to the registration procedure under evaluation. The quality of a model-based registration procedure can be measured by comparing the geometry parameters that on the one hand have been preset for generation of virtual radiographs and on the other have been determined by the algorithm under evaluation. In addition, evaluation of any registration procedure (including non-parametric registration methods, such as elastic warping) can rely on the similarity of the virtual baseline and registered virtual follow-up radiographs, where the bias of structured noise resulting from altered beam pathways is again known *a priori*.

A relative comparison between two grossly different generic methods of image registration prior to subtraction is applicable if both methods are assessed as described above and the individual results are compared, either in terms of geometry or image similarity. The latter case is exemplified in Figure 8. The three subtraction images have been generated from

Figure 5c,d using different methods for *a posteriori* registration. The differing amounts of structured noise that are visible in all images can be transferred into figures of any similarity measure and used for objective evaluation.

Discussion

Virtual radiographs provide a suitable method and means to quantitatively assess the quality of computer-based registration procedures, which are incorporated into third-generation subtraction systems. Once the TACT volume representation of the desired object is generated, realistic radiographs can be simulated from any point of view. The number of projections as well as the size of the sampling aperture determines the resolution of the TACT volume in the z-direction. Although this limitation restricts the angular deflection of the source for virtual X-ray projections, it does not limit the suitability of virtual radiographs in general. Note that in clinical situations, the positioning of the X-ray tube head must be both precise and relatively reproducible to enable subtraction of serial free-hand radiographs, which also limits angular tolerance.

Because the tube, object, and imaging device are not real, any one of them can easily be assigned any desired property. For instance, the virtual source may project X-rays for virtual radiography from any focal spot geometry. Enlargement of the focal spot size will blur the virtual radiographs. In addition, virtual X-ray beams can be created according to Poisson-distributed quantum noise to simulate low-dose radiography.

Furthermore, 3D image manipulation techniques applied virtually to any dental model facilitate realistic simulation of lesions or other changes that may have taken place between the virtual exams. Note that these manipulations are not limited to the rigorous removal of local bone or tissue by means of a virtual drill. More sophisticated models of tissue modification for bone reconstruction or caries also can be applied. If these models are carefully selected with respect to Criterion 2, virtual radiographs might also become a gold standard for diagnostic procedures, e.g., for caries detection.

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