TECHNICAL NOTE

Development of a new dental panoramic radiographic system based on a tomosynthesis method

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The objective of this study was to develop a new practical method to reconstruct a high-quality panoramic image in which radiographers would be free from the onerous task of correctly locating the patient's jaws within the image layer of the panoramic unit. In addition, dentists would be able to freely select any panoramic plane to be reconstructed after the acquisition of the raw scan data. A high-speed data acquisition device was used with a CdTe (cadmium telluride) semiconductor detector and a sophisticated digital signal-processing technique based on tomosynthesis was developed. The system processes many vertical strip images acquired with the detector and generates a high-resolution and high-contrast image. To apply the tomosynthesis technique to the acquired strip images correctly, the actual movement of the panoramic unit was measured, including the X-ray tube and detector, in a scan using a calibration phantom and the authors generated a shift amount table needed for the shift-and-add tomosynthesis operation. The results of the experiments with a PanoACT-1000 panoramic unit, which was a PC-1000[®] panoramic unit fitted with a high frame rate semiconductor detector SCAN-300FPC[®], demonstrated the capability of a tomosynthesis technique which, when applied to the strip images of a dry skull phantom, could change the location and inclination of an imaging plane. This system allowed the extraction of an optimum-quality panoramic image regardless of irregularities in patient positioning. Moreover, the authors could freely reconstruct a fine image of an arbitrary plane with different parameters from those used in the original data acquisition to study fine anatomical details in specific locations.

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Introduction

In dental panoramic systems,¹ the teeth and jaws should be located in the centre of the image layer, which is defined as a layer that images the teeth with sufficient spatial resolution and contrast. If the patient's jaws are located away from the central plane of the image layer, the spatial resolution of panoramic images rapidly decreases and the quality of the image degrades. In addition, since the shape and size of the jaws vary among individuals, some patients may not fit perfectly into a given panoramic unit's image layer.

Therefore, the positioning of a patient's jaws to obtain an optimum-quality image is burdensome for radiographers. Moreover, all teeth do not conform to the central plane of the image layer, that is, each tooth axis forms a different angle (axial inclination) to the central plane, and thus it is not always possible to acquire the optimum fine image quality at both ends of all of the teeth, namely the root apices and coronal, occlusal and incisal surfaces. One of the solutions to this problem is to apply the concept of tomosynthesis, an idea which is very old^{2,3} and has been introduced to panoramic imaging by several groups.^{4,5} Unfortunately, none of the available detectors were capable of acquiring data at a high speed, and thus no commercially successful dental panoramic system with tomosynthesis has been achieved thus far.

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In 2008 Spartiots and Pantsar⁶ developed a semiconductor detector that was available for dental panoramic radiography and presented the basic concept for reconstructing an image acquired with the semiconductor detector. Semiconductor detectors such as cadmium telluride (CdTe), which work at room temperature, provide a new paradigm in the field of dental panoramic imaging because of their high-speed data acquisition, high spatial resolution, high sensitivity and good linearity between incident X-ray energies and output signals. With such high-speed data acquisition, we can obtain many strip images each acquired at a slightly different direction to the teeth as determined by the movement pattern of the rotation centre. This enables us to develop a new method of forming panoramic images using a traditional tomosynthesis algorithm that simply involves shifting and adding.⁷ Ideally, with this concept we can freely reconstruct images of a curved dental arch after obtaining the raw data with the standard data acquisition procedure, assuming average jaw size and tooth inclinations.

The aim of the study was to develop a practical method to reconstruct a high-quality panoramic image with a tomosynthesis method, in which radiographers are free from the burden of setting up a patient's jaws at the exact central plane of the image layer of the panoramic unit and dentists can freely select a panoramic plane to be reconstructed after acquisition of the raw data.

Materials and methods

To develop the new system the Spartiots's basic method was used and the shift amount calculated, which is needed to reconstruct an image with a tomosynthesis method. To calculate the shift amount, a clinically used system was modelled as accurately as possible. The mathematical background for obtaining the shift amount is shown in Appendix 1. Figure 1 shows a simple geometrical scheme of a panoramic system with a moving rotation centre. An X-ray tube rotates around isocentre O along trajectory T_S with rotation radius R_S , and a strip detector rotates around the same isocentre along trajectory T_D with rotation radius R_D . The movement of the detector is synchronized with the X-ray source opposed to the detector with a constant speed, where the isocentre moves along trajectory T_O . In this simulation model the X-ray tube and the detector rotated with $R_S = 423$ mm and $R_D = 125$ mm with a constant speed around the moving rotation centre from -90 to $+90$ degrees. The definition of the angular position is shown in Figure 1. The number of acquired frames per degree was assumed to be 20 and the total number of frames acquired was 3600. The isocentre moved during data acquisition along trajectory T_O in Figure 1. It was presumed that this system had a narrow area detector with size 6.4×151 mm. The pixel size of a strip image acquired with the

Figure 1 The geometry of a panoramic imaging system. The isocentre moves along pre-defined trajectory T_O .

detector was assumed to be 0.1×0.1 mm. With the moving rotation centre this system made an image layer which consisted of $D = 30, 32, 44, 52, 60, 72$ and 78 mm for the directions of $0, \pm 15, \pm 30, \pm 45, \pm 60, \pm 75$ and ± 90 degrees, respectively. The image layer assumed here was identical for a panoramic X-ray unit PC-1000[®] (Panoramic Corporation, Fort Wayne IN).⁸ In this simulation the shift amounts that focus the central plane in the image layer for particular angular positions were calculated. Three cases were evaluated in terms of the size and location of a jaw: one is just on the central plane in the image layer, and the other two are cases in which the location of the plane moves towards the inside or outside by 5 mm. Moreover, magnification factors were calculated for particular angular locations for the above three conditions regarding the size of the jaws.

Next, a new calibration phantom was developed to ensure the quality of the panoramic image. With this calibration phantom the actual shift amount was measured for each angular position. This is required because the image layer and movement pattern of both the X-ray source and the detector may not be exactly the same in individual panoramic units in clinical situations, even though the unit is shipped from the same manufacturer. Thus, measurement of the actual movement for each panoramic unit is necessary for reconstructing a high-quality image. Figure 2 shows the calibration phantom. As shown in Figure 2c, the phantom consisted of a thin brass plate and a polymethyl methacrylate (PMMA) block with a trapezoidal shape. The centre part of the PMMA block was hollowed to decrease the effect of attenuation of X-rays passing through the PMMA material. The PMMA block had a surface whose angle to the horizontal plane

Figure 2 The calibration phantom with a brass plate to determine the shift amount at each angular position. (a) A plan for the arrangement, with a dotted line indicating the pre-designated image layer for PC-1000. (b) Top view of the phantom arrangement. (c) The dimensions of a polymethyl methacrylate (PMMA) block

was 45 degrees, on which was pasted the thin brass plate: size 46×6 mm and thickness 0.2 mm. We hollowed out 13 2.5×2.5 mm crosses from the brass plate, and positioned these crosses 3 mm apart. We placed the PMMA blocks with brass plates along the standard dental arch such that the seventh cross was positioned just on the central plane of the image layer described in the literature,⁸ and each block was placed exactly on a line whose angle to the anterior axis was 0, ± 15 , ± 30 , ± 45 , ± 60 , ± 75 , ± 90 and ± 97.5 degrees, as shown in Figure 2a. Although the whole phantom consisted of 15 blocks, only 9 blocks were attached to one side from -15 degrees to 97.5 degrees to measure the shift amount in order to eliminate blurring caused by the blocks attached to both sides, as shown in Figure 2b. Thus, two data sets were obtained (from -15 to 97.5 degrees and from -97.5 to $+15$ degrees) and combined for the evaluation of the shift amount of both sides. To acquire the strip images with the calibration phantom, we used the panoramic unit under the same conditions as in clinical situations. However, we used an aluminium plate with a thickness of 20 mm to reduce the intensity of X-rays because there was no attenuation material in the phantom. Once a number of strip images had been acquired with this phantom and the optimal shift amount selected for corresponding angles visually, and data saved as a table, we could reconstruct a suitable panoramic image with the tomosynthesis method by referring to the table, even though the source and the detector do not rotate at an exactly constant speed. In addition, if the shift amount was increased or decreased according to the size of the jaws, it is possible to easily change the location of the focused image plane, which better fits the jaws of the patient being scanned.

To realize the new concept the authors developed a panoramic X-ray unit which was designated as "PanoACT-1000[®]"; this was a combination of a PC-1000 and a solid-state detector SCAN-300FPC[®] (Oy

Ajat Ltd, Espoo Finland). The size of the strip image acquired was 64×1510 pixels (6.4×151 mm) and the operational frame rate was 300 fps. The X-ray tube and the detector rotated around the moving isocentre with an exposure of 12.5 s over a 195 degree scan for data acquisition. Thus the number of acquired frames per degree was 20 and the number of frames acquired in total was 3900. The isocentre moved with an almost constant speed during data acquisition, as previously described.⁸ The rotation radius of the X-ray source and the detector was 423 mm and 125 mm, respectively. Lengths D in Figure 1 at specified angles 0, ± 15 , ± 30 , ± 45 , ± 60 , ± 75 , ± 90 and ± 97.5 degrees to the anterior direction (the longitudinal axis in Figure 2⁸) were 30, 32, 44, 52, 60, 72, 78 and 82 mm, respectively. The tube voltage was 75 kV and the tube current was 6 mA. By using this system data were acquired with the newly developed calibration phantom mentioned above and a dry skull phantom (Dental phantom PTU-1-A[®], Kyoto Kagaku Co Ltd, Kyoto, Japan) and clarified the performance of the method under conditions similar to those experienced clinically. A dedicated software was developed designated "PanoACT" to synthesize a number of strip images into a focused panoramic image with a shift-and-add technique. In addition, a new method was developed for tilting the image plane and this was installed in the panoramic system software. This enables a dentist to observe the teeth more clearly from the tip of the roots to the crowns in an image of a tooth.

Results

Figure 3 shows the shift amounts calculated with Equation 1 in Appendix 1, which focuses the central plane in the image layer for particular angular positions. This figure shows three cases in terms of the size and location of a jaw: just on the central plane in the image layer, and inside or outside the central

Figure 3 The shift amount at each angular position calculated with Equation 1. The shift amount needed for the tomosynthesis varies according to the location of the image plane. Three cases are shown as regards the position of the image plane to be reconstructed: one is just on the central plane in the image layer and the other two are cases in which the location of the plane moves towards the inside or outside by 5 mm

plane by 5 mm. In Figure 3 the shift amount changes mainly because of the distance between the isocentre and the central plane of the image layer. The shift amount changes when the size of the jaws (*i.e.* the position of the image plane being focused on) changes. Figure 4 shows magnification factors for particular angular locations for the above three conditions as regards the size of the jaws. The result shows that the factor is almost the same even if the size of the jaws changes.

Figure 5 shows panoramic images of calibration phantoms acquired with the standard image layer for

Figure 4 The scaling factor at each angular region is from 0 to 90 degrees. Three cases are shown regarding the position of the image plane to be reconstructed: one is just on the central plane in the image layer and the other two are cases in which the location of the plane moves towards the inside or outside by 5 mm

PC-1000. Figure 5b is a synthesized image focused on the central plane of the image layer that is pre-designated for this panoramic unit. The seventh crosses from the top, which are located just on the central plane of the image layer, are imaged clearly for all directions. In contrast, if the size of jaws is decreased, *i.e.* the position of the image layer, by 5 mm virtually with the tomosynthesis method (Figure 5a), or increased by 5 mm virtually (Figure 5c), the ninth cross or fifth cross is imaged clearly. This shows that the change in the shift amount corresponded to the change in the location of the focusing plane in the image layer. Figure 6 shows the effect of tilting the image plane to four angular positions: 0, 30, 60 and 90 degrees (a, b, c and d, respectively). In each angle the image plane is tilted by 0, 15, 30 and 45 degrees (A, B, C and D, respectively) by changing the shift amount column by column with the tomosynthesis method. The brass plates tilted by 45 degrees, designated D, were imaged clearly about all the crosses in all directions.

Figure 7 shows an example of malpositioning of a patient's jaws using a dry phantom. The jaws of this skull phantom were intentionally positioned behind the pre-designated standard dental arch shape at a distance of 18 mm, thus producing distortions and blurring, especially at the incisors (Figure 7a). By using the PanoACT software, a high-quality panoramic image was reconstructed as if the patient's jaws had been positioned correctly in the position of the pre-designated image layer of the PC-1000, as shown in Figure 7b. Figure 8 shows the tilting effect of the image plane. Figure 8a shows an image reconstructed with standard parameters and Figure 8b shows an image as if the patient's jaws are located outside the pre-designated image plane by 5 mm. Figure 8c shows an image tilted 11.3 degrees with the PanoACT software with respect to the central plane in the image layer. In this image the whole of each tooth is clearly imaged from the root apices to the coronal surfaces.

Discussion

The principle of image formation in conventional panoramic imaging systems is very simple;^{9,10} that is, with a narrow X-ray beam passing through a patient's jaws, the structure on a curved plane in the dental arch is projected onto a moving film or sensor through a slit. The X-ray source and a film cassette or sensor opposed to the source rotate around the patient while the film moves synchronously with the source. In this system, structures outside the curved focal plane are blurred, and a relatively narrow layer in the dental arch is imaged with high resolution and high contrast, making patient positioning very critical. To obtain an image of teeth and jaws without overlapping of structures, cone beam CT (CBCT) is sometimes the modality of first choice. However, the detectors used for CBCT (for example, an image intensifier or a solid-state detector) have a size

Figure 5 Panoramic images of the calibration phantom. The nine brass plates on the polymethyl methacrylate block are located from the -15 to 97.5 degree positions. (a) Image focused on the plane which is smaller than the central plane (shown by a dotted line) by 5 mm. (b) Image focused on the central plane in the image layer. (c) Image focused on the plane which is larger than the central plane (shown by a dotted line) by 5 mm

limitation, mainly due to cost, and we sometimes have to cope with the truncation problem of projection data caused by a small field of view. In CBCT, metals and dense materials produce beam hardening and star artefacts which interfere with accurate interpretation of disease. In addition, the dose to the patient is increased compared with panoramic imaging.¹¹ However, the panoramic imaging system is a reasonable modality in terms of image quality, patient dose and cost for most dental practices. Recently, several manufacturers and researchers of panoramic imaging modalities have adopted digital imaging sensors instead of a film–screen detector, such as a two-dimensional sensor with a slit, a linear sensor and a strip two-dimensional sensor.^{12–16} These digital sensors improve the quality of panoramic images in terms of the spatial resolution and contrast resolution, but the basic idea underlying these approaches is the same as that of the conventional panoramic system with a moving film and a slit, and thus the problem in positioning patients' jaws remains and

the sophisticated digital image processing availability is not possible. On the other hand, if a semiconductor detector is adopted such as CdTe connected to Complementary Metal Oxide Semiconductor (CMOS) instead of the scintillator and the charge-coupled device

Figure 6 Panoramic images of the calibration phantom. (a)–(d) The angular locations of the brass plate from 0 to 90 degrees. A, B, C and D show the tilted angles to the central plane, which is vertical to the horizontal plane. A, 0 degrees; B, 15 degrees; C, 30 degrees; D, 45 degrees

Figure 7 (a) An original panoramic image focused on the central plane in the image layer, where the jaws are located intentionally behind the central plane of the image layer by 18 mm. (b) The panoramic image adjusted optimally with the PanoACT software

Figure 8 (a) An original panoramic image focused on the central plane of the image layer. (b) The synthesized image on the outside plane of the central plane by 5 mm. (c) The synthesized image tilted by 11.3 degrees to the central plane

(CCD) detector, it is possible to achieve a new data-processing scheme with the help of high-speed data acquisition in the range of 300 fps. With the detector many narrow images are acquired first, and with these images a panoramic image is reconstructed using tomosynthesis, that is shifting and adding (or overlapping and adding) these narrow images. The requirements in the tomosynthesis of panoramic imaging are data acquisition with a high frame rate, high sensitivity, high spatial resolution and wide dynamic range. The SCAN-300FPC detector used in the system enabled 20 frames/degree of rotation while the X-ray tube and detector rotate around the patient in 12 s. The detectable angular region was from -102.5 to $+102.5$ degrees to the patient in the PanoACT-1000[®] system. With this technology, the shift amount can be easily changed for each strip image after data acquisition, so that the radiographer does not have to position the patient's jaws in an exact pre-determined position. The addition of narrow two-dimensional images increases the contrast of the structural details of the teeth or jaws. Because the CdTe detector has high sensitivity compared with other scintillation materials, the patient dose can be reduced during an examination. Once the actual shift amount for

establishing the focal image plane with the calibration phantom has been measured and the values for each corresponding angle stored, the image plane that best fits the patient's jaw can be reconstructed with the acquired strip images. Thus, retakes or insufficient radiation settings are avoided. In addition, it is possible to use the raw scan data to freely tilt the image plane in order to place any whole tooth in sharp focus by changing the shift amount column by column in the image matrix, as shown in Figure 8. In the PanoACT-1000 the focal plane of a patient's panoramic image is fundamentally selected automatically with the acquired image, but a radiographer or dentist can select the plane manually to investigate specified teeth in detail. For the adjustment of the vertical plane inclination, the operation is performed manually. These new post-processing procedures provide more useful information to the dentist without any additional X-ray examinations. Moreover, the quality of the raw data obtained with the CdTe semiconductor detector was superior to the CCD detector in terms of contrast resolution because of the linearity between the fluence of detected X-rays and output signals. As mentioned before, the pixel size of the detector was 0.1×0.1 mm, and so the fine structural details of the teeth and jaws are imaged very clearly, especially when the contrast of the panoramic image is enhanced. The system utilizes the advantages of digital signal processing and state-of-the-art semiconductor technology.

In conclusion, the authors developed a new panoramic radiography system, in which a large number of vertical strip images acquired with a semiconductor detector were used to reconstruct high-quality images using the concept of tomosynthesis. The newly developed calibration phantom was useful for deciding the true shift amounts in each panoramic unit. The new system made it possible to reconstruct any selected arbitrary plane for a specific dental arch shape and to incline this image plane freely.

References

1. Langland OE, Langlais RP, McDavid WD, DelBalso AM. *Panoramic radiology* (2nd edn). Philadelphia: Lea & Febiger, 1989.
2. Des Plantes Z. Eine neue method zur differenzierung in der roentgenographie. *Acta Radiol* 1932; **13**: 182–192.
3. Grant DG. Tomosynthesis: a three-dimensional radiographic imaging technique. *IEEE Trans Biomed Eng* 1972; **19**: 20–28.
4. Groenhuis RAJ, Webber RL, Ruttimann UE. Computerized tomosynthesis of dental tissues. *Oral Surg Oral Med Oral Pathol* 1983; **56**: 206–214.
5. McDavid WD, Welander U, Dove BS, Tronje G. Digital imaging in rotational panoramic radiography. *Dentomaxillofac Radiol* 1995; **24**: 65–75.
6. Spartiots K, Panssar T. Dental extra-oral x-ray imaging system and method. US patent 7336763, 2008.
7. Dobbins JT III, Godfrey DJ. Digital X-ray tomosynthesis: current state of the art and clinical potential. *Phys Med Biol* 2003; **48**: 65–106.
8. Francisco EE, William CS, Hayakawa Y, Smith M, Farman AG. image layer characteristics of the PC 1000 (mark II). *Oral Radiol* 1997; **13**: 11–21.
9. Welander U. A mathematical model of narrow beam rotation method. *Acta Radiol Diagn* 1974; **15**: 305–317.
10. Welander U, Shiojima M, McDavid WD, Tronje G. A general mathematical theory of rotational panoramic radiography incorporating non-rotational scanographic methods. *Oral Radiol* 1990; **6**: 69–88.
11. Frederiksen NL, Benson BW, Sokolowski TW. Effective dose and risk assessment from computed-tomography of the maxillofacial complex. *Dentomaxillofac Radiol* 1995; **24**: 55–58.
12. Whaites E, Brown J. An update on dental imaging. *Br Dent J* 1998; **185**: 166–172.
13. Benediktsdottir IS, Hintze H, Petersen JK, Wenzel A. Image quality of two solid-state and three photostimulable phosphor plate digital panoramic systems, and treatment planning of mandibular third molar removal. *Dentomaxillofac radiol* 2003; **32**: 39–44.
14. Farman AG, Farman TT. A comparison of image characteristics and convenience in panoramic radiography using charge-coupled device, storage phosphor, and film receptors. *J Digit Imag* 2001; **14**: 48–51.
15. Farman AG, Farman TT. Extraoral and panoramic systems. *Dent Clin North Am* 2000; **44**: 257–272.
16. McDavid WD, Dove SB, Welander U, Tronje G. Direct digital extraoral radiography of the head and neck with a solid-state linear x-ray detector. *Oral Surg Oral Med Oral Pathol* 1992; **74**: 811–817.

Appendix 1

The concept of tomosynthesis is illustrated in Figure 9. When the X-ray source is located at S_1 , a given point A on the dental arch shape (U-shaped area in Figure 1) in the image layer is projected onto the detector at position $P_A(S_1)$. Suppose the source rotates by a very small angle θ and moves to position S_2 ; a projected position of point A moves to $P_A(S_2)$ in the detector. If several vertical strip images of the teeth with a high frame rate for a small angular region are acquired, it is possible to increase the contrast of given point A using the principle of the tomosynthesis. That is, there are several strip images, in which point A is projected on to the detector at a slightly different angle, and the image data is shifted with a fixed amount defined by each image so as to overlap position A and add them, the image contrast can be increased at position A in the image layer. At the same time, a given point away from the image layer is scattered with this procedure. In the case shown in Figure 9, if the strip image acquired is shifted for source position S_2 by distance $C_2 P_A(S_2)$ to the left and added to the image acquired for S_1 , a vertical line including point A is overlapped and other structures are scattered around the line including point A. This is the basic concept of so-called tomosynthesis, and in this method, shifting and addition are fundamental operations to form a high-contrast image focused on a specified image plane. The shift amount x is calculated by the relationship $(R_S + D \cos \theta)$: $D \sin \theta = (R_S + R_D) \cdot x$, that is

$$x = \frac{R_S + R_D}{R_S + D \cos \theta} D \sin \theta \quad (1)$$

where D is the distance between the isocentre and the point of interest on the dental arch shape (Figure 1). In this case, the magnification factor changes with D during the movement of the isocentre, so it is normalized for the size of strip images with scaling factor F , which is normalized with the distance at the front teeth ($D = R_D$), as follows:

$$F = \frac{R_S + D \cos \theta}{R_S + R_D} \quad (2)$$

Thus, when making a panoramic image from a number of strip images acquired with a panoramic unit which has a moving rotation centre, compensation is

Figure 9 The tomosynthesis scheme in dental panoramic imaging

Figure 10 The lateral view of a panoramic imaging system. The teeth make angle ϕ with the image plane

required for the size of acquired strip images with scaling factor F and shift the compensated image by $x \cdot F$ at each angular position of the detector and add these images so as to focus a specified plane in the image layer.

In addition, to tilt the image plane locally to the central plane in the image layer by ϕ (i.e. $\tan \phi = \alpha / \beta$) as shown in Figure 10, it is necessary to change the shift amount of the acquired strip images column by column and add to another strip image. That is, the shift amount for a focal plane depends on D , and if distance D is decreased by α , the column of interest in an image can be focused allowing construction of a tilted plane with strip images acquired with a standard procedure.