RESEARCH ARTICLE

Obstacles in spatial evaluation of CBCT-reformatted panoramic imaging

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Objectives: Conventional panoramic radiography (cPR) underlines procedure-related limitations in the display of objects. CBCT is presumed to overcome these constraints. To virtualize a cPR view, reformatted panoramic images (rPIs) can be generated. This study evaluated the rPI with regard to its susceptibility to sterical object deposition in comparison with cPR.

Methods: A specially developed implant model with dental implants each of 4.0-mm diameter and 11.0-mm length was deposited by shift, rotation and tilt of 5.00 mm (± 0.01 mm) of horizontal shift and 5.0° ($\pm 0.167^\circ$), respectively, on a highly precise goniometer rotation table, and cPRs and rPIs were generated. Automated evaluation of the cPRs was carried out using a specially developed software. rPIs were processed and analyzed by a semi-automated image analysis.

Results: Object deposition lead to distortive effects in the rPI analogue to cPR, but they appear in display only. Objects illustrated in the rPI were dimensionally correct, but sterical relations are elusive. Results are obtained for the horizontal shift, declination and reclination, lateral tilt and rotation.

Conclusions: Distortions within the rPI represent the illustration of the hyperbolic-shaped layer out of the three-dimensional data set. With this study, we demonstrated these procedure-related inherent but practically underestimated consequences. Effects of sterical object malpositioning must be compensated by the observer by adequate virtual adjustment of the processed layer. Accurate virtual adjustment leads to vertical dimensions. Sterical relations, e.g. angulation of two objects, are irretraceable unless precisely referenced.

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Introduction

Conventional panoramic radiography (cPR) succumbs to inherent procedural limitations such as inconsistent magnification, geometric distortion, deposition and poor definition of objects situated outside the focal

trough. This results in a non-anatomic display of the radiographed anatomic structures. These restrictions inherently occur to a certain extent even if the patient is exactly positioned within the individualized focal trough.¹ In addition to the known physico-technical insufficiencies of the cPR and varying anatomical prerequisites, patient malpositioning increases aberrations

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in the display. This limits the cPR in precisely interpreting spatial relationships.²

Since accurate information of radiopaque structures is decisive in precise radiologic evaluation, three-dimensional (3D) imaging modalities were assumed to overcome the constraints of conventional radiography.

In the late 1990s, CBCT was introduced to dentistry and maxillofacial surgery.³ Besides the option of evaluating the whole reconstructed volume in sagittal, coronal and axial planes as multiplanar reconstructions (MPR), CBCT provides the option to visualize two-dimensional pictures as reformatted panoramic images (rPIs). rPIs represent MPR in a specially curved layer, meeting the criteria of cPR in display. It can be applied in either a predefined manner or individualized by the observer. This mode has been assumed an alternative to cPR.⁴

Figures 1 and 2 show clinical cases and depict the vulnerability of subsequent rPIs to set virtual layers in a tilted generated volume. The hyperbolic-shaped layer was—promptly to be seen—adjusted according to clinical needs. In this study, we precisely evaluated rPIs in a constant predefined layer generated from CBCT data sets in displaying spatial relationships as well as their vulnerability to object malposition. The addressed

Figure 1 Clinical case of virtually planned insertion of a single implant using SimPlantPro™ (Materialise, Belgium): (a) aspect from below, (b) subsequent reformatted panoramic image and (c) anterior view.

Figure 2 Clinical case of virtually planned insertion of three implants using SimPlantPro™ (Materialise, Belgium) the (a) aspect from below, (b) subsequent reformatted panoramic image and (c) anterior view.

questions were whether CBCT-derived rPI is able to overcome:

- (a) the procedure-related inherent problems of cPR and
- (b) the significant impact of patient malpositioning on cPR.

Methods and materials

A ProMax 3D™ device (Planmeca, Helsinki, Finland) was used to facilitate the option of generating cPR and CBCT without changing the object position. This enables a maximum in comparability of findings in CBCT-derived reformatted imaging to cPR. The device utilizes a charge-coupled device and was run with proposed settings for the acquisition of data in adults. A voltage of 90 kV and a current of 12 mA were applied. cPR was run under 54 kV and 16 mA. The voxel size amounted

to $100 \times 100 \times 100 \mu\text{m}$ in the largest acquisition volume at $80 \times 80 \text{ mm}$.

A model of 12 vertically thus parallel arranged dental implants (Osseo Speed™; Dentsply, Mannheim, Germany), each of 4.0-mm diameter and 11.0-mm length and in the position of the first incisor, the canine and the first molar, was placed in the focal image layer of the PR/CBCT device. Maxillary and mandibular simulated dental arches were positioned on the same sagittal level to simulate the edge-to-edge bite situation during cPR. The upper and lower implants were vertically spaced with resin plates at 15.0 mm, simulating a clinical distance of two dental crowns. For the simulation of tilt and inclination, this implant model was mounted on a two-axis goniometer (GNL20/M; Thorlabs Inc., Newton, NJ), allowing precise movements *via* micrometer screws. The rotation point was adjusted within the occlusal plane.

The goniometer was centrally mounted on an XYR table (XYR1/M; Thorlabs Inc.), enabling a sagittal and transverse shift as well rotation within the horizontal plane.

The micrometer screws had a graduation of $10 \mu\text{m}$ regarding progressive feed and of 10 arcmin according to 0.167° regarding rotation. The construction was adjusted and mounted on the manufacturer locking device for a definite rigid fixation, as described before.² Highly precise movements in five degrees of freedom (sagittal and transverse shift, rotation, inclination and tilt) were facilitated *via* micrometer screws (Figure 3). Every quality of the malposition was simulated separately.

The adjustment criteria were as follows: the point of vertical rotation of the XYR table was matched with the intersection point of the virtual straight line from the centre of the condyles, with the contralateral canine

positions representing the geometric centre of the cPR focal trough. The position of the implant in the upper canine position was verified by the beam guides in the neutral position.

A series of nine data sets for cPR and CBCT were taken in the unchanged implant model position. All images in cPR were taken in the standard focal trough adjustment. The cPR and rPI of the implant model in the central position and without angulation served as the reference image. This facilitated a maximum approximation of the rPI to the cPR in the optimal positioned model.

For consecutive reformatted images, a reproducible plotting scale was used. The Planmeca Romexis® software v. 2.1.1.R was applied. For rPI evaluation, a pre-set standard focus layer was three-dimensionally adjusted to the position of the implants.

The standard focus layer was uniformly three-dimensionally positioned in every CBCT data set for the malpositioned implant model.

Various malpositions were simulated separately and images were taken at highly precisely in the malposition of 5.00 mm ($\pm 0.01 \text{ mm}$) of the horizontal shift and 5.0° ($\pm 0.167^\circ$) rotation, tilt and declination/reclination. In all resulting images, all implants have been evaluated for axial length, width, angulation to horizontal plane and position in the horizontal and vertical axis.

All pictures were exported as *.tif files. The digitally acquired cPRs underwent an automated image analysis. This was performed by a special developed software for the standardized evaluation of every individual panoramic image. The derivation of the grey values was used to find local contrast by means of a Sobel operator.²

Results

Automated analysis was feasible in all cPRs and resulted in comparable precise implant outlines. In the rPIs, diffuse implant outlines compromised automated processing, so a firmware-based semi-automated evaluation was performed (Romexis software v. 2.1.1.R).

Horizontal shift

In the horizontal implant misalignment, identical rPIs could be processed by an adequate spatial adjustment of the focus layer (Figure 4a–c). The traceable displacement of the implant model was virtually reproducible. With the measuring tools implemented in the Romexis software, assessment of the length and diameter was feasible despite blurred edges. Measurements resulted consistently in 4.0-mm width and 11.0-mm length for all displayed implants, representing a truthful illustration of the implant model (Figure 4a,b). In contrast to this, in cPR, horizontal shifts resulted in remarkable and inhomogeneous distortions and displacement of the illustrated implants. Aberrations in the display were most striking in sagittal shifts. Inconsistent horizontal distortion was up to 43%, from 5.0-mm posterior to 5.0-mm anterior shift, and an inconsistent vertical distortion

Figure 3 Schematic illustration of the XYR table with a two-axis goniometer. Yellow arrows show the shift and rotation in plane. Red arrows illustrate the declination, reclination and tilt. The tip marks the common rotation point placed in the occlusal plane. For colour image see online.

Figure 4 (a) The reference image (central position of the implant model, no angulation or rotation), (b) 5-mm anterior shift (consistent implant dimensions and interimplant distances) and (c) overlay of the processed conventional panoramic radiography from 5-mm posterior (purple) and anterior shift (blue); none of them show “real” dimensions. For colour image see online.

showed a maximum value of 4.2%. Horizontal shift led to considerably horizontal and vertical implant displacement within the cPR (Figure 4c).

Change in inclination

Declination and reclination of the implant model resulted in the same distortion (convex and concave bending of the horizontal plane) in cPR and rPI (Figure 5a–d). Implants displayed were inconsistently angulated and displaced; interimplant distances varied in cPR.

Contrary to that the implant images revealed consistently true dimensions in rPI concerning the width and height as well as interimplant distances.

Lateral tilt

When tilted laterally, an S-shaped distortion by aspect resulted similarly in cPR and rPI (Figure 6a–d). Contrary to cPR, in rPI, all the implants measured were consistently 4.0 mm in width and 11.0 mm in length. The calculated interimplant distance

Figure 5 (a) A reformatted panoramic image (rPI) of the 5° declined implant model; (b) rPI of the 5° reclined implant model; (c) conventional panoramic radiography (cPR) image of the 5° declined implant model; and (d) cPR image of the 5° reclined implant model. Displayed measurements in (a) and (b) are examples.

Figure 6 (a) A reformatted panoramic image (rPI) tilted right by 5°; (b) rPI tilted left by 5°; (c) conventional panoramic radiography (cPR) image tilted right by 5°; and (d) cPR image tilted left by 5°. Displayed measurements in (a) and (b) are examples.

remained at 15.0 mm. In cPR, dimensions changed considerably.

Rotation

Rotation led to inconsistent displacement of implants out of the reformatted curved layer, resulting in aberrant images (Figure 7a–d). Consequently, manual adjustment became mandatory. Implant dimensions and interimplant distances remained unaltered. The relative motion in an unadapted rPI corresponded with the aspect in cPR.

Discussion

Limitations in precisely interpreting spatial relationships are inherent in cPR, since magnification within the tomographic image is inconsistent owing to different object detector distances. Inhomogeneous distortion and non-anatomical display of structures have to be taken into account during the evaluation of cPRs.^{5,6} It has recently been demonstrated that there are only certain points in the focal trough at which vertical and

Figure 7 (a) A reformatted panoramic image (rPI) rotated right by 5°; (b) rPI rotated left by 5°; (c) conventional panoramic radiography (cPR) image rotated right by 5°; and (d) cPR image rotated left by 5°. Displayed measurements in (a) and (b) are examples.

horizontal magnification are consistent, achieving zero distortion.¹

rPI was proposed as an alternative to cPR by Mischkowski and co-workers.⁴ The group experienced higher quality in cPR than in rPI owing to noise, poor contrast and artefacts. Extinction and hardening artefacts caused by dense structures like dental implants were critically discussed in CBCT^{7,8} and consecutively appear in rPI as well.

The claim for cross-sectional images in planning the insertion of implants has been the subject of an ongoing debate. It has been researched ever since a position article of the American Academy of Oral and Maxillofacial Radiology emphasizing on rectangular settings was published in 2000.⁹

Our study on rPI as a particular imaging modality in CBCT elucidates malposition-related image distortion. Owing to the reproducible precise technical setting of our trial, we demonstrated minimal error. The effect of each particular direction of malpositioning has been evaluated separately. Schulze *et al* claimed digital measurements as sufficiently accurate for clinical use, specifying that reliable measurements had been obtained for linear objects. The presented images can be considered as consistent and reliable in clinically relevant scales.¹⁰ The data of the present study confirm these findings in part. It has to be kept in mind that there is a substantial information loss in dependence of layer thickness of the focal trough chosen by the observer,¹¹ because rPI cannot stand alone as a summation image representing all available information out of the volume. The often unreliable interpretation of root angulation from cPR, especially if inclined buccolingually, can be visualized on reformatted CT images.¹² The measurement of angles in rPIs is not permissive because perpendicularity cannot be simultaneously secured in two different regions. An automated adjustment would be preferable, but this does not exist to date.

The results of our study demonstrate that implant size was assessed as varying in cPR, but consistent in the voxel-based rPI. This is in accordance with findings in the clinical situation of implant size measuring on cPR and rPI.¹³

A comparison of non-referenced images is difficult and thus favouring CBCT, which allows adjustment and a further exploration of the volume.¹⁴ Structures of interest must be observed selectively and dynamically.

Recently, our group demonstrated that it is illegitimate to claim a certain precision or reliability level of measurements in panoramic images.² According to the present data, it is illegitimate to compare different rPIs without highly precise virtual adjustment of the dental arches and individual adaptation of the focus layer. An alternative in order to achieve a better orientation within 3D volumes could be provided by maximum intensity projections, as shown recently;¹⁵ but, these demand highest spatial perception of the observer.

MPR should be evaluated dynamically in all three dimensions and throughout the whole data set. This is

especially valid for the rPI, since it is a processed artificial image out of a 3D data set with a hyperbolic-shaped plane only arbitrarily adapted to the shapes of the jaws. The shown distortions represent the illustration of the hyperbolic-shaped layer and are therefore inherent. Because the distortive effects in rPI appear only in the illustration, we like to emphasize the term “pseudodistortion”.

Reliable statements determining spatial relationships can be made with regard to limitations of the voxel size and the applied processing algorithm. Achievement of perpendicularity in the observed region is mandatory.

The rPI outperformed the cPR, if observed dynamically. If not tilted, malpositioning in the x- or y-axis of the examined objects could have resulted in nearly identical rPIs, but defining of reference planes was necessary. If evaluating a tilted structure, accurate adjustment of the hyperbolic-shaped layer within the volume is mandatory, since it determines the generated image.

The effect of sterical object malpositioning can be compensated by the observer by adequate virtual adjustment of the processed layer. Accurate virtual adjustment leads to truthful dimensions of the displayed objects. Therefore, in rPI, point-to-point measurements are permissive, whereas in cPR measurements, they are unreliable. The assessment of angulation of two objects must be questioned.

“General” adjustment of the whole jaw does not make the grade of sterical relations reliable. The clinical application of rPI-based guided implantation carries the risk of unintentional incorrect position and angulation of implants, if no accurate adjustment during virtual planning is secured. Profound knowledge and awareness of the entity and limitations of rPI as a specially generated virtual layer out of a 3D data set is mandatory in order to avoid unintended and imperceptible misinterpretation.

Conclusions

The demonstrated distortions within the rPI represent the illustration of the hyperbolic-shaped layer out of the 3D data set and therefore are inherent. They are “pseudodistortions”, because they appear in the illustration only. On the basis of the presented data, the significance of rPI for spatial evaluation as superior to cPR in all aspects must be questioned.

Clinical relevance

The virtual rPI carries restrictions in interpretability, especially with regard to sterical relations. The observer has to be aware of these limitations particularly in implant planning, virtually designing implant guides, evaluation of inserted implants or giving an experts opinion.

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