Intraoperative and dynamic 3D rotational X-ray imaging
Carelsen, B.

Citation for published version (APA):

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Download date: 27 Mar 2019
Chapter 7

4D rotational X-ray imaging of wrist joint dynamic motion

Bart Carelsen, Niels H. Bakker, Simon D. Strackee, Sjirk N. Boon,

Mario Maas, Jörg Sabczynski, Cornelis A. Grimbergen,

Geert J. Streekstra

based on:

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*Medical Physics 2005 Sep;32(9):2771-6*
7.1 Introduction

To evaluate wrist functioning the analysis of 3D patterns of movement of the carpal bones in the wrist joint is crucial. In vitro 3D animations and models of the complex joint motion were deduced from the motion of extremities using external reference frames, which are not applicable in in vivo studies. [1-3] A review of literature on in vivo carpal analysis on carpal bones image can be found in Mooijen et al.[4] State of the art 3D imaging methods allow only a static display of carpal bones.[5; 6] Repeated imaging of 3D carpal bones at multiple static poses of the hand provides only an animated movement pattern. However, a dynamic movement pattern of carpal bones may deviate from its animated counterpart due to neuromuscular control and dynamic properties of ligaments and cartilage in the wrist. From 2D video radiographic observations we know that clinically significant abrupt changes in orientation and position of carpal bones can occur during dynamic movement.[7] These abrupt changes do not occur during static poses in the absence of wrist movement used for animated imaging.

In vivo dynamic measurements of 3D movement patterns were performed with 2D (biplane) fluoroscopy [8; 9] registration to 3D CT images, however only applied to the knee, which is less complex to match since there are only two bones. Biplane dynamic 3D imaging of the more complex wrist requires several X-ray modalities and sophisticated matching algorithms.

In this paper a method for 3D dynamic imaging of the wrist is introduced, which uses a modified mobile C-arm system with 3 Dimensional Rotational X-ray (3D-RX) capabilities. This 3D-RX system allows acquisition of a number of X-ray projection images along a semicircular arc, which are reconstructed into a 3D data set similar to CT.[10] The open geometry of the C-arm provides a compliant workspace for several postures. For 4-Dimensional Rotational X-ray (4D-RX) we propose using the 3D-RX system to make a series of time resolved volume reconstructions of an object that is forced into a cyclic motion. This approach is closely related to the image acquisition method applied in ECG-gated 3D-rotational coronary angiography (3DRCA) with multi-slice computed tomography or respiratory gated cone-beam CT. [11-15] Instead of the retrospective gating used in these methods, we apply prospective synchronization of the image acquisition with the cyclic motion of the wrist. This procedure yields a series of volume reconstructions of the wrist at different phases of its cyclic motion.

To investigate the feasibility of 4D-RX we performed tests with a phantom to obtain image quality as a function of imaging parameters. In addition the image quality of our setup is illustrated by imaging a post mortem wrist.
7.2 Imaging of dynamic motion patterns

In its conventional application for imaging of static objects a mobile C-arm 3D-RX system[16] acquires a series of X-ray projection images from different angles. This is done with a prototype BV Pulsera (Philips Medical Systems, Best NL) mobile C-arm system. The C-arm is motorized to make a propeller movement over a semicircular track at constant speed meanwhile acquiring projection images. For adequate 3D-RX reconstruction, an angle of 180° + cone angle is covered. The dose is automatically adjusted during the run to obtain optimal images from the image intensifier TV system. The pulsed images, acquired at constant acquisition frequency, are sent to a modified 3 Dimensional – Rotational Angiography (3D-RA) workstation.[10] The image geometry of the projection is calibrated beforehand and is used in the reconstruction. The projection images, corrected for image and geometry distortions, are then reconstructed to a 3D dataset, which is a 3D-RX reconstruction representing a tomographic X-ray image. The reconstruction is done with a modified Feldkamp filtered back projection algorithm.[17] The dose automation, voxel scaling and beam geometry (not all what is irradiated is also reconstructed) provide that there is no absolute radio density scale like the Hounsfield scale in CT but this does not affect the image quality measurements.

When the object is moving, a 3D image at a certain phase in the motion cycle can be obtained if all projection images within a set used for reconstruction are acquired at the moment that the object passes the same point in the motion cycle. When multiple sets of projection images are acquired during a movement cycle, multiple 3D-RX reconstructions of the moving object at different motion phases are obtained, together forming the 4D-RX image. For 4D-RX, a mobile C-arm is rotated around a cyclic moving object that has frequency \( f_{\text{object}} \) or period \( T_{\text{object}} = f_{\text{object}}^{-1} \). During rotation of the C-arm, X-ray projection images are acquired of the moving object that is located in the centre of rotation. The acquisition of projection images is performed at a fixed frequency \( f_{\text{x-ray}} \) or period \( T_{\text{x-ray}} = f_{\text{x-ray}}^{-1} \) (see Fig. 1).

To ensure multiple projection images at the same phase of the motion, the frequency of the cyclic object motion \( f_{\text{object}} \) and the acquisition frequency \( f_{\text{x-ray}} \) of the X-ray system must be synchronized and follow the relationship

\[
f_{\text{x-ray}} = n_{\text{phases}} \cdot f_{\text{object}},
\]

where \( n_{\text{phases}} \) is the integer number of phases of the object motion cycle that are imaged. The projection images belonging to the same phase of object motion are grouped. For each phase an equal number of projection images are obtained

\[
n_{\text{projections}} = \frac{f_{\text{x-ray}} \cdot D_{\text{x-ray}}}{n_{\text{phases}}} = \frac{\Phi_{\text{C-arm,total}}}{\Delta \Phi_{\text{C-arm}}},
\]

with \( D_{\text{x-ray}} \) the total duration of the 3D-RX scan, \( \Phi_{\text{C-arm,total}} \) the total C-arm rotation, and \( \Delta \Phi_{\text{C-arm}} \) the C-arm rotation in one object motion cycle (Fig. 1). Each element in the set of \( n_{\text{phases}} \) reconstructions has its own phase in the motion cycle and together the reconstructions form a dynamic 3D image, i.e., a 4D-RX image.
Fig. 1. A time fragment of the 4D-RX acquisition. The C-arm is rotated around the cyclic moving object (with period $T_{\text{object}}$). Meanwhile projection images are acquired with a period of $T_{\text{x-ray}}$. Projection images from identical phase of the object motion are acquired on regular time intervals $n_{\text{phases}} \cdot T_{\text{x-ray}}$ corresponding to C-arm rotation angle intervals $\Delta \Phi_{\text{C-arm}}$.

7.3 Equipment

For the image acquisition, a BV Pulsera 3D-RX prototype is used. The system is modified to perform a motorized rotation over $200^\circ$ starting and ending at an approximately horizontal position (X-axis see Fig. 2). The system is able to take pulsed fluoroscopic images with pulse length between 8-13 ms and with acquisition frequencies ($f_{\text{x-ray}}$) in the range 1-25 Hz, with a maximum of 375 images or maximal 30 seconds scan duration. The X-ray pulses have an amplitude of 60 mA and automatic voltage control. In the case of a wrist, the voltage stabilizes around 50 kV, resulting in an effective dose of only 0.1 mSv. The projection images are sent to a modified 3D-RA release 3.2 workstation for reconstruction (Philips Medical Systems, Best, The Netherlands). Beforehand the system is calibrated in two steps as described in Koppe et al.[18; 19] Firstly, the pincushion distortion of the image intensifier, the S-distortion due to the magnetic field and the focal spot are calibrated; secondly, the C-arm geometry is calibrated. The workstation reconstructs a 3D data set from all projection images in a spherical field of view with a diameter of 18 cm. The 3D-RX reconstruction is a volume image of 256x256x256 voxels, which are isotropic with a size of 0.7 mm.
The PSF is not isotropic partly due to radial under-sampling. In the case of a semicircular arc + cone angle, parker weighting has to be applied.[20] This procedure with a rotation around the Y-axis (propeller rotation of the C-arm see Fig. 2) yields the best spatial resolution in the horizontal plane (XY plane Fig. 2), similarly like Wu et al.[21] However, the Parker weighting absence in our reconstruction causes an additional blur on the X-axis. This results in the PSF to be best in the Z direction. This is parallel to the direction of motion of the object and allows optimal investigation of possible motion blur.

A movement device was developed to impose a cyclic motion to an object. A DC motor drives a mechanical transmission to move the object 40° up and down (Fig. 2). The entire movement lies within the volume of reconstruction. The DC motor with speed reduction is feedback controlled to ensure a constant frequency of motion. The cycle of the object is tracked with an electronic sensor to enable synchronization with the 3D-RX system. Object movement and X-ray signal are displayed on a digital oscilloscope and verified. After manual synchronization, the acquisition of the projection images is started. Next, the projection images are sorted and reconstructed as described in the previous section.

Fig. 2. Schematic drawing of the movement device in two positions. A side view, B front view. In panel A (YZ plane) he motor and gears are shown; on the right the crank driving the upward-downward movement of the hand xobject. This part is situated in the volume of reconstruction (the shaded circle) and is therefore wrapped in low density plastic. Panel B shows (XZ plane) the C-arm’s detector rotating from the positive to the negative X-axis over the positive Z-axis while the object moves up and down along the Z-axis.
7.4 Experiments

Deviations in the object movement result in an unmistakable failure of 3D-RX reconstruction containing apparent motion artefacts. If the synchronization conditions are not obeyed the X-ray and the motion will be out of phase in every 3D-RX set; this yields large motion artefacts in every reconstruction. Reliability of this system is imposed by the motor controller. In our experiments, two measurements (one from either experiment) with a clear visible deviation were redone.

Experiment 1: Number of projection images
In our prototype system the $D_{x-ray}$ is fixed and $f_{x-ray}$ is set to obtain the highest possible number of projection images, which means that the number of projection images available for each reconstruction is inversely proportional to the number of phases (Eq. 2.). In other words there is a trade-off in our system between the image quality (determined by the number of projections that can be used for reconstruction) and the temporal resolution of the system (the number of phases of object motion that can be obtained). If the number of projection images for a single reconstruction increases, the number of available phases decreases and at the same time the frequency of the object also increases (Eq. 1).

Preliminary experiments in a static situation showed that using less then 25 projection images yielded unacceptable 3D-RX image quality. The upper boundary for the number of images is determined by the object speed which should not exceed 1.5 Hz for clinical reasons. Furthermore, all 3D-RX projection image sets should cover the total propeller angle $\Phi_{C-arm, total}$ of 180° + cone angle (together 196°).

To see the effect of the number of projection images on the contrast resolution and spatial resolution, two object frequencies are used. At these object frequencies, reconstructions of a bullet and rod phantoms (Fig. 3) are generated with the settings from Table 1 (Measurement 1 and 2). The bullet and rod phantom is routinely used to quickly check image quality of rotational X-ray systems. As a reference, a high quality Measurement 3 is done on the same phantom in a stationary situation. To investigate the severity of the motion artefacts in Measurement 1 and 2, Measurements 4 and 5 are performed with identical number of input projections but without motion.

The contrast resolution can be characterized by the Contrast-to-Noise Ratio (CNR). A cube of $16^3$ voxels is analyzed in a homogenous part of the phantom as well as in air. The standard deviation which was comparable in air and in the phantom material was taken as the noise figure and the mean value difference between air and the phantom as contrast number. The CNR is determined by dividing the contrast number by the noise.
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The spatial resolution in terms of the Full Width at Half Maximum (FWHM) of the Point Spread Function (PSF) was measured by means of the Edge Spread Function (ESF) as described by Buhr et al.[22] A non-isotropic 3D Gaussian was used as a model of the PSF to define a theoretical ESF, which is fit to edges in the image. The FWHM of the PSF was determined on 10 edges in all three directions, measuring approximate 25 contours per edge. The streak artefacts sometimes interfered with the ESF determination, therefore 10 measurements were done. Noticed should be, as described in the former section, the PSF is expected to be smaller in the direction of motion due to the acquisition geometry and absence of Parker Weighting.

Table 1. Measurement setup and results of image quality evaluation for investigation of the influence of the number of projection images on the reconstruction. In all measurements \( f_{\text{ray}} = 12.5 \text{ Hz} \) and \( D_{\text{ray}} = 30 \text{ seconds} \).

<table>
<thead>
<tr>
<th>M</th>
<th>( n_{\text{phases}} )</th>
<th>( f_{\text{object}} )</th>
<th>Pulse</th>
<th>( n_{\text{projecti}} )</th>
<th>( \phi_{\text{C-arm, total}} )</th>
<th>CNR</th>
<th>PSF/ ( \text{motion} \pm \text{SD} )</th>
<th>PSF/ ( \text{L motion} \pm \text{SD} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>1.38 Hz</td>
<td>10 ms</td>
<td>41</td>
<td>199°</td>
<td>3.0</td>
<td>0.7±0.1 mm</td>
<td>1.5±0.3 mm</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>1.13 Hz</td>
<td>10 ms</td>
<td>34</td>
<td>201°</td>
<td>2.9</td>
<td>1.0±0.2 mm</td>
<td>2.2±0.5 mm</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0 Hz</td>
<td>13 ms</td>
<td>251</td>
<td>202°</td>
<td>6.9</td>
<td>0.6±0.1 mm</td>
<td>1.1±0.2 mm</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0 Hz</td>
<td>13 ms</td>
<td>41</td>
<td>202°</td>
<td>4.0</td>
<td>0.6±0.1 mm</td>
<td>1.4±0.2 mm</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0 Hz</td>
<td>13 ms</td>
<td>34</td>
<td>202°</td>
<td>3.5</td>
<td>0.7±0.1 mm</td>
<td>2.2±0.3 mm</td>
</tr>
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</table>

Note. – CNR = Contrast-to-Noise Ratio. PSF = Point Spread Function. SD = standard deviation. // motion = Parallel to the motion (in the Z direction). L motion = Averaged over the directions orthogonal to the motion (the X and Y direction).

Fig. 3. The position of the bullet and rod phantom on the movement device. The bullet and rod phantom is a 3³ cm³ Plexiglas cube with 3 orthogonal metal rods (cylinders with diameter 2 mm and height 30 mm) and 3 metal bullets with diameter 4 mm.
Figure 4 and Table 1 show the use of 41 instead of 34 images yields improvement of image quality both for contrast and spatial resolution. The stationary measurements 4 and 5 show minor CNR improvement compared to their similar moving Measurements 1 and 2.

In table 1 the $PSF_{L\text{ motion}}$ (the FWHM of the PSF averaged over the X and Y axis) is shown as well as the $PSF_{//\text{ motion}}$ (the FWHM of the PSF parallel with the motion direction, i.e. Z axis). The $PSF_{L\text{ motion}}$ and $PSF_{//\text{ motion}}$ FWHM together give a description of the spatial resolution, all measurements should be compared with measurement 3. This shows that deterioration of image quality is mostly due to sub-optimal sampling of the projection images when comparing measurement 1 and 2 with their static counterparts’ measurement 4 and 5.

Influences of motion artifacts will affect the FWHM of $PSF_{//\text{ motion}}$ mostly. The motion blur is most evident in Measurement 2 as from the $PSF_{//\text{ motion}}$ can be noticed. Measurement 1 does not show significant deviation from its static counterpart Measurement 4.

**Experiment 2: 4D-RX imaging of a post mortem wrist**

A post mortem wrist is imaged in 4D-RX to show the obtainable image quality. The wrist is fixed in the movement device. Settings are identical to Experiment 1, Measurement 1. Figure 5 shows three of the 9 phase's volume rendered. The same phases are shown in sagittal slices at the height of the lunate in Figure 6. For both Figures the visually optimal window/level settings are used.
Fig. 5. Three volume renderings of the post mortem wrist of experiment 2. The three images represent three different phases in the joint motion cycle. The viewing angle is located midway between a coronal and a sagittal view. In the volume rendering some parts of the movement device, the support, hinge and a small metal bullet, are also imaged.

Fig. 6. Three sagittal slices (thickness 0.7 mm) of the post mortem wrist of experiment 2 at the height of the lunate. The phases of the slices correspond to those of the volume renderings of Fig. 5.

Although both volume rendering and slice views show artifacts (Figs. 5 and 6), the anatomical structures of the carpal bones are clearly visible. Most of these streak artifacts and shadowing are due to sub optimal sampling and surrounding structures. The contrast of the bony structures is sufficient not to be influenced significantly by the artifacts. A comprehensible representation of the 3D joints’ kinematics is contained in the 3 different phases of motion that are shown.
7.5 Discussion

Dynamic imaging of the wrist and other joints for diagnostic purposes may be of great help for assessing functional disorders of the joint. Current imaging systems cannot make dynamic 3D images of the moving wrist. Therefore, we developed a method called 4D-RX, in which a prototype mobile rotational X-ray system is used together with a device suitable for imposing synchronized cyclic movement of the wrist.

The presented method is expected to provide better insight into dynamic motion patterns than 2D video fluoroscopy. Due to the three dimensional dynamic character and potential for quantitative measurements of 3D motion patterns by means of segmentation and matching, our method is potentially a valuable support for diagnosis of wrist disorders. State of the art quasi dynamic CT imaging of the carpals lacks representation of the true clinically relevant dynamic situation, since hysteresis and acute changes in motion patterns will not be revealed. Our system is able to image a dynamic forced motion pattern of the wrist provided the pattern reproduces over a number of cycles.

The number of input projection images needed for adequate 3D-RX reconstruction quality was examined with a bullet and rod phantom. The image quality was analyzed with the CNR and the PSF. The FWHM of the PSF was determined from the ESF fitted to the image data. The absence of Parker weighting in our reconstruction processes causes anisotropy in the PSF. Both the PSF and CNR show that the 4D-RX image quality is similar to 3D-RX image quality when using 41 images. The main deterioration of these images is due to the low number of projection images and not to the motion of the object. The use of 34 images yields a considerable decrease in image quality, especially in spatial resolution parallel to the direction of the movement. The lesser image quality obtained with 34 images could also be a synchronization error but this is unlikely when looking at the images of Figure 4.

In the current system there is a trade-off between the temporal resolution and the reconstruction quality. Using a larger number of input projection images for reconstruction may further improve future image quality. This may be achieved by increasing the duration of the scan and increasing the total number of acquired projections. For clinical use, the object frequency should be limited to provide patient comfort. This can be achieved by either decreasing the acquisition frequency or increasing the number of phases (Eq. 1.). In both cases, the duration of the scan should be increased to ensure a sufficient number of projections for reconstruction (Eq. 2.).

The choice for the use of this mobile 3D-RX system is its flexibility in number of input projections and movement and its mobility to comply with the experimental setting. The main hardware related disadvantages are the limited duration of the scan (max 30s) and the 8 bit detector. Other 3D C-arm systems, like floor- and ceiling mounted C-arms used for interventional radiology, have better hardware but are less flexible in use.

For further validation of the method technical exploration of the validity of the
assumption of motion cycle reproducibility is also needed. Moreover, addition of other clinically relevant motion patterns and clinical compatibility of the method are subjects for further study. Apart from the wrist joint this method can be used in a wide range of joints including elbow and feet, which would only require a small modification of the movement device.

In this paper, we showed the feasibility of imaging 3D dynamic motion patterns of cyclically moving carpal bones in the wrist. Despite the presence of noise and sub-optimal sampling, anatomical structures are clearly recognizable in the wrist experiment. We expect that 4D-RX will pave the way to improved assessment of joint disorders by detection of 3D dynamic motion patterns in joints.

References