Roentgen stereophotogrammetric analysis to study dynamics and migration of stent grafts

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CHAPTER 2

Technique of RSA and FRSA

History of RSA

Roentgen Stereophotogrammetric Analysis (RSA) has a long and successful history in orthopedic surgery. It is used to evaluate joint prostheses for signs of aseptic mechanical loosening, the most common cause for revision surgery in long term follow-up.[1-3] A highly accurate measurement method is required to detect this detrimental effect at an early stage. Early detection allows for early evaluation of new implants, coatings and cement in small patient groups before large scale introduction in clinical practice.[4,5] RSA has a very high accuracy and digitization of the technique with specialized RSA software enabled easy, fast and accurate analysis of stereo images. For this reason, RSA has evolved to become the gold standard for evaluation of micro-motion of the prosthesis with respect to the bone after joint replacement surgery.[6-11]

Principles of RSA

The essence of RSA can be compared to stereo vision of human eye sight: two images of an object are simultaneously acquired by the eyes. Each image is taken from a different angle. The brain compares these images and is able to determine the position of the object in space as compared to the human body. "Calibration" of the brain to determine the position of the object is done by trial-and-error experience.

RSA also uses two simultaneously acquired, calibrated images to determine the three dimensional position of markers in the human body. During surgery, reference markers are placed inside the body. The prosthesis is inserted and the relative position and orientation of the prosthesis can be assessed by comparing its position and orientation to that of the reference markers. When comparing consecutive RSA images over time, a change of position of the prosthesis as compared to the reference markers can be detected. This way, migration of the prosthesis can be detected.

RSA uses two still images to perform this reconstruction. It is therefore ideal for follow-up after surgery, to determine position changes of prostheses. Obviously, this technique with still images cannot be used to assess a dynamic, rapidly changing position that occurs in the pulsatile environment of the vascular system. Analysis of a dynamic situation requires rapid sequence (calibrated) imaging.

Technique of RSA

Markers

As discussed previously, distinct prosthesis markers and reference markers are required to perform RSA. To apply RSA to the endovascular surgery environment, the stentgraft and the aorta have to be marked accordingly. The stentgraft markers used to position the graft during placement can be utilized for this purpose. Reference markers need to be attached to the aortic wall to serve as reference markers. In **CHAPTERS 4, 5 and 6** the issue of aortic reference markers will be addressed in more detail.

The RSA set-up

To acquire a stereo image for RSA, two roentgen films or detectors, positioned under the patient, are exposed by two synchronized roentgen tubes. A calibration box is positioned between the patient and the films to produce a coordinate system and enable measurements (Figure 1).

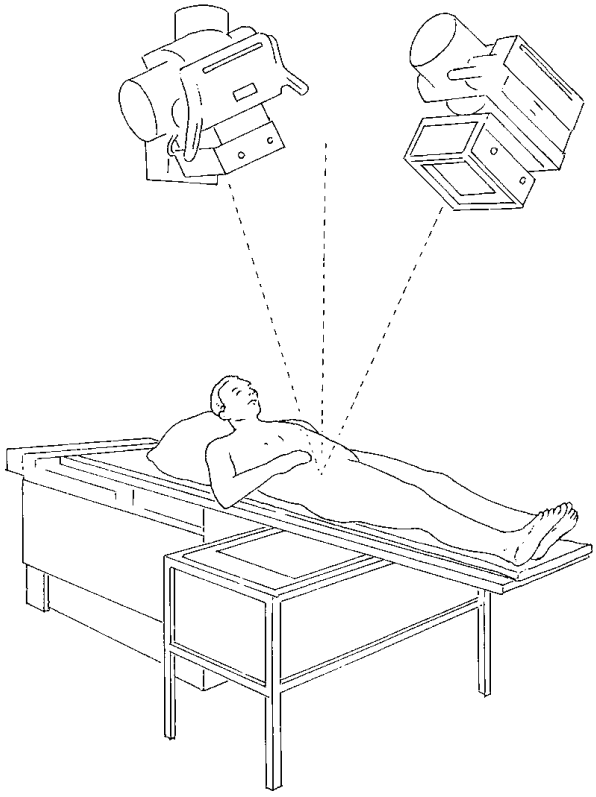

Figure 1. RSA imaging setup. The reference and control markers are in the box under the patient. The radiographic films are placed directly under the box.

Two synchronized Roentgen tubes

Two standard hospital roentgen tubes are used to acquire the images. The two roentgen tubes are positioned approximately 1.60 m above the film and at a 20° angle to the vertical (Figure 1 and 2). The exposure of the films is synchronized by simply pressing the exposure buttons of the two machines at the same time. Because this is done by hand, exact simultaneous exposure of the films may not be achieved. This could lead to motion artifacts and result in inaccurate measurements. This type of error is especially possible in an endovascular surgery setting where the markers are continuously displaced by the pulsatile motion of the blood vessels. This issue is further addressed in **CHAPTER 4**.

Calibration box

Since it is the goal of RSA to perform measurements to determine the three dimensional position of markers, the images have to be calibrated. This enables three important steps in the image analysis: a) the position of the images (films / detectors) as compared to each other has to be determined; b) a laboratory coordinate system has to be added to the image to define distance in the image; c) the position of the two roentgen tubes has to be determined as compared to the films. After these steps have been performed the position of all components of the set-up is known including their relation to each other. These steps will be discussed separately below.

Image calibration is performed with the help of a calibration box positioned between the patient and the films (Figure 1). The box is made of carbon fiber sandwich plates. This material is chosen because it is insensitive to changes in room temperature and humidity. Furthermore, carbon fiber plates are radiolucent. The dimensions of the box are 70 x 46 x 24 cm. The top and bottom layers of the box contain tantalum markers to perform the calibration. These markers are positioned with a computer controlled device and the position of these markers is known within a few micrometers. The bottom layer contains *fiducial* markers. The top layer of the box contains the *control* markers. The use of the calibration box markers will be elucidated below.

Scatter grids

As the roentgen beam passes through the body, it is partially absorbed by the tissues. The X-rays that pass through the body (the primary bundle) generate the image. Some X-rays however, are neither absorbed nor pass straight through the body but only change direction and scatter. These X-rays produce a grey mist in the image and therefore reduce the image quality. To reduce this effect, a scatter grid can be used to filter out these scattered X-rays.

Roentgen tube setting and radiation dose

The roentgen tubes are set to maximize contrast of the metal graft and reference markers. Next to RSA, the images can be used for stent fracture detection. Soft and bony tissues are of less interest in the image. The radiation dose for a stereo RSA image of an abdominal aortic stentgraft is 0.3 mSv, which is roughly one sixth of the yearly natural background radiation. This amount of radiation is dwarfed by the radiation dose received for a standard 3-phase contrast enhanced CT used for regular follow-up after endovascular aneurysm repair, which is approximately 17 mSv.

Digital RSA

After acquisition of the stereo image, the films are digitized and loaded into the RSA software (Model Based RSA software, MEDIS Specials BV, Leiden, The Netherlands) on a personal computer. Digitally acquired images are loaded directly into the software.

The software automatically detects the markers and performs the calibration and analysis steps. Every step in the marker recognition process can be verified manually in a user friendly way. This method has been validated and was described previously in mathematical detail.[8-12]

Calibration of the set-up

First the *fiducial* and *control* markers of the calibration box are detected. With the known positions of these markers the two images can be virtually repositioned next to each other in the same way as they were positioned under the patient. The *fiducial* markers on the bottom of the box are used to define the laboratory coordinate system. Furthermore, these markers are used to virtually transform the image from the plane of the film to the lower plane of the box. Now that the position of the two films is known relative to each other and the transformation of the films has been calculated as well as the laboratory coordinate system for the image pairs, the position of the two roentgen foci can be reconstructed.

The known positions of the *control* markers (Figure 2 thin arrow, top of the box) can be matched to the projections of these markers on the film (Figure 2 thick arrow). The marker and its image on the film are, by definition, in one line with the roentgen focus. These lines are called projection lines (Figure 2 thick lines). By calculating the point of intersection of different projection lines through the control markers and their images, the position of the roentgen focus is determined (Figure 2 top right).

Now that the position of the films and the roentgen foci is known as well as their relation to each other, the set-up calibration is complete.

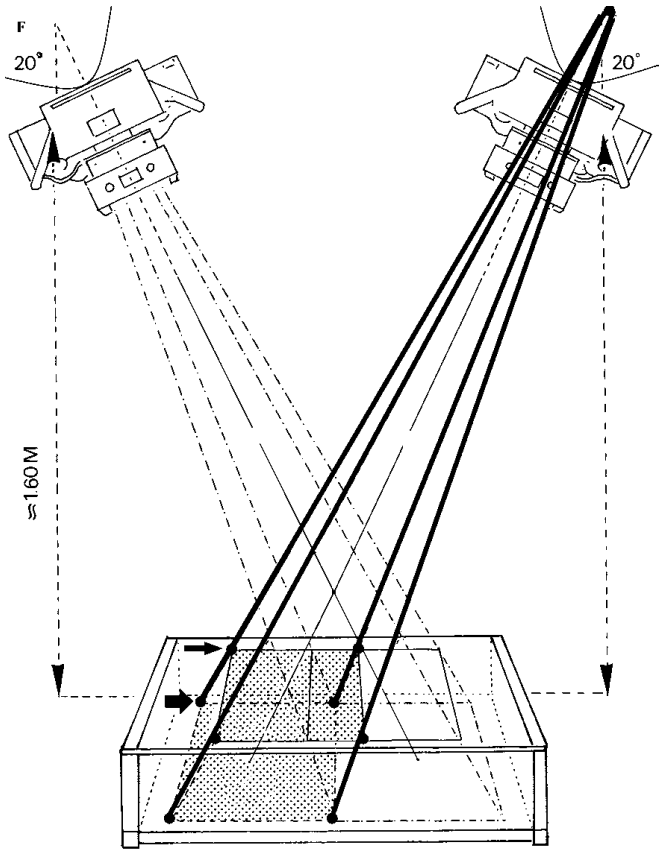

Figure 2. Reconstruction of the position of the Roentgen foci (F). The control markers (thin arrow, top layer of the box) project an image on the film (thick arrow). The point of intersection of the projection lines of the control markers (thick lines) defines the Roentgen focus (F).

Calculation of three-dimensional marker position

After calibration of the set-up, calculation of the position of a marker relative to other markers in the body becomes an equation with one unknown value: the position of the foci and the films is known, and therefore the position of the marker can be calculated.

To determine the three-dimensional position of a stentgraft marker or reference marker, a projection line is calculated through (the now known position of) the roentgen focus (Figure 3: F) and the projection of the marker on the film (Figure 3 projection B and C). This is done for both projections on the two films (Figure 3 line 1 and 2). By calculating the point of intersection of the two lines(Figure 3: A), the three-dimensional coordinates of the marker becomes clear, relative to the laboratory coordinate system. In reality, the projection lines do not intersect but cross, due to minute measurement errors. Therefore, the marker is positioned in the middle of the shortest distance between the two projection lines. This phenomenon of crossing instead of intersection is called the crossing line error and is given by the software for each calculated three dimensional marker position. It can be used as an internal control for measurement error:

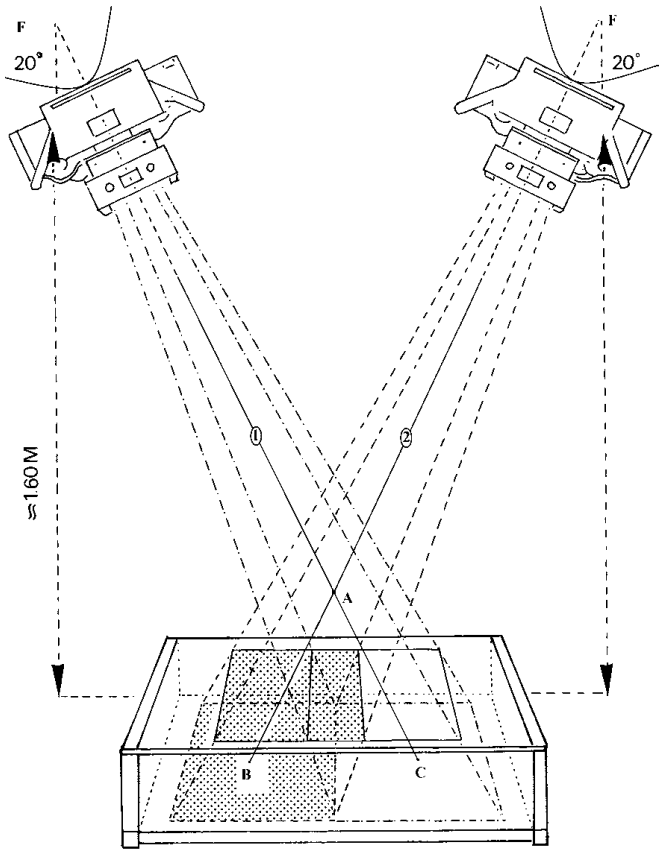

Figure 3. Schematic drawing of the RSA technique. Graft marker A gives projections B and C on the films. With a known focus position, projection lines 1 and 2 can be reconstructed. The calculation of intersection of 1 and 2 in space gives the position of A.

the smaller the crossing line error, the more accurate the calibrated set-up and measurement. A typical crossing line error is 0.02 mm.

Because the calibration is performed with the aid of the box under the patient, each new image is calibrated according to its laboratory coordinate system. Positioning of the patient does not influence the measurement because the distance between reference marker and graft marker is determined according to the coordinate system.

FRSA

Fluoroscopic roentgen stereophotogrammetric analysis (FRSA) is a novel application of RSA principles and technique to high definition digital stereo fluoroscopy with a high frame rate (images per second). This enables imaging and quantification of marker motion, for instance during the cardiac cycle. Until recently, equipment with these specifications was not available. In June 2005 a Siemens Axiom Artis dBc imaging system was placed in the Leiden University Medical Center, and we developed and validated a method to accurately quantify three

dimensional marker motion at a high frame rate.[13] This has been impossible up to now, despite advanced imaging systems like (ECG-gated) CT and MRI. FRSA could therefore be of great value to the knowledge of stentgraft motion and stentgraft improvement.

As explained above, RSA with still images is constrained to longer term follow-up because only one image can be produced at a time. In order to quantify marker motion, several images need to be acquired per second, comparable to cinematography. These images need to be calibrated in a similar way as RSA images.

The FRSA set-up and calibration process is different from regular RSA at several points in the process.

The FRSA set-up

The set-up consists of two C-arms with digital flat panel detectors (Siemens Axiom Artis dBc imaging system, Siemens, Forcheim, Germany). The C-arms are positioned at a 90° angle, producing a lateral and a postero-anterior (PA) image (Figure 4). In contrast to standard RSA, the 90° angle is chosen for two reasons: a) practical reasons, since this is a standard setting in the machine; b) for maximum accuracy, since on theoretical grounds a 90° angle will result

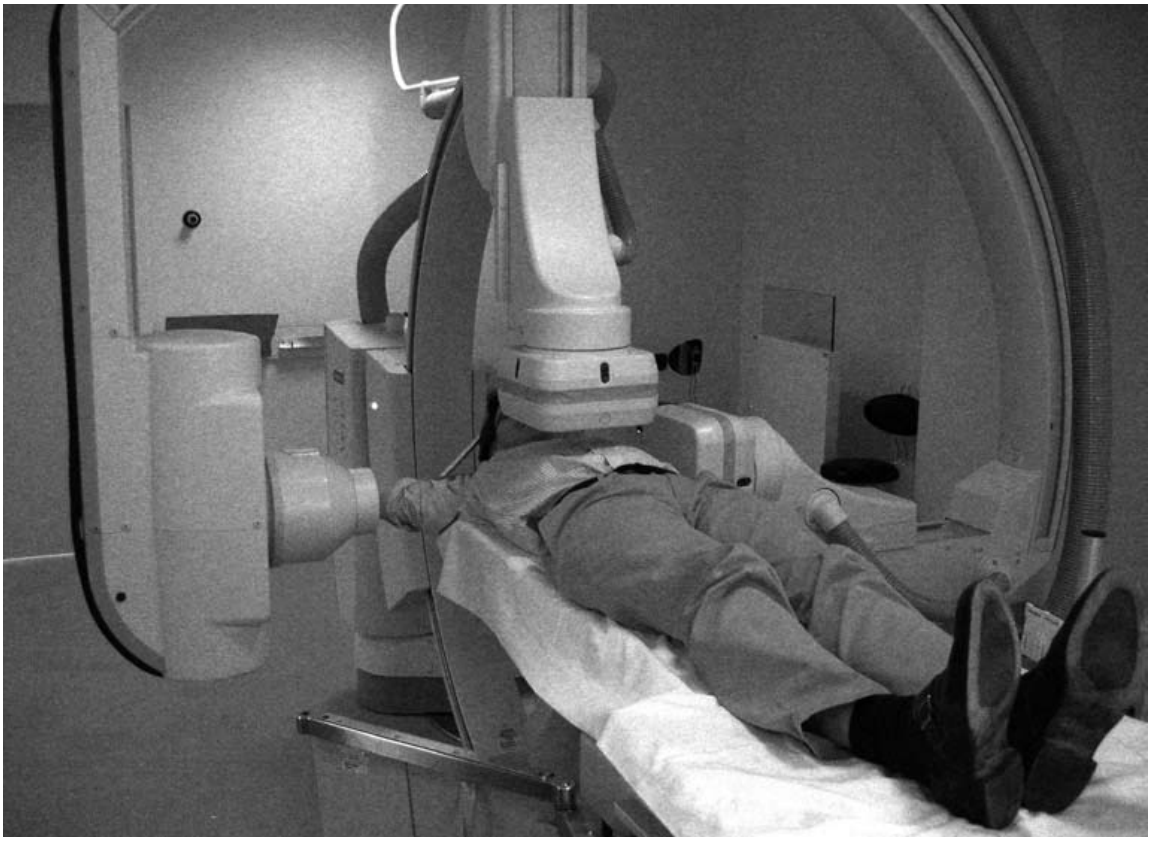

Figure 4. Clinical set-up of the bi-plane fluoroscope.

in a maximum angle of the imaging on the direction of the marker motion (as little out of plane motion as possible). To maximize the field of view, the detectors are placed as close to the patient as possible. The set-up acquires high definition digital stereo images of the body at a frame rate of 30 bi-directional frames per second. The stereo images are acquired as two alternate single images (i.e. 60 single frames per second). The exposure time of each image is approximately 4 ms. The pause between the PA and the lateral image is approximately 12.7 ms.

The image pairs are analyzed using Model-based RSA software (MB-RSA, MEDIS specials, Leiden, The Netherlands) to calculate the relative 3-D marker positions.[8-11] No image reconstruction is required before analyzing the image pairs.

Calibration of the FRSA set-up

To calibrate the set-up, an acrylic block is used with markers at precisely known positions (Figure 5). A FRSA (stereo) image of this block is acquired with the set-up. Afterwards, the process, as described above, of calculation of the position of markers with the MB-RSA software is reversed. This time the position of the markers is known and therefore the position of the foci and the detectors can be calculated, as well as their position in relation to each other. The patient is positioned in the set-up without changing the C-arm positions. Once the position of the foci and the detectors is known, this can be fed into the software and images of the patient can be analyzed in the standard way as described for RSA, revealing the positions of the markers on the stent-graft.

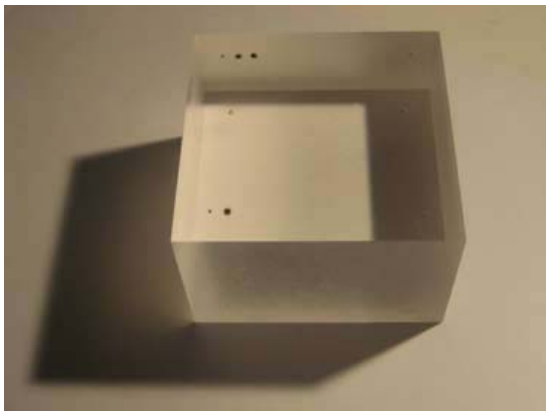

Figure 5. Calibration object. Acryllic block, dimensions w x d x h: 8 x 8 x 5 cm. In every corner one tantalum marker, diameter 1mm. In the top layer three extra markers, diameter 2mm for ease of identification of the different markers.

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