3D ROTATIONAL ANGIOGRAPHY OF TRANSPLANTED RENAL ARTERIES

A CLINICAL AND EXPERIMENTAL STUDY

by

GAUTE HAGEN

UPPSALA
UNIVERSITET

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Uppsala University
Department of Oncology, Radiology and Clinical Immunology
Section of Radiology
Akademiska sjukhuset
SE-751 85 Uppsala, Sweden
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ABSTRACT


Three-dimensional rotational angiography (3D-RA) is an established method within the field of interventional neuroradiology. The method has also a great potential in other areas with a complicated arterial anatomy. The purpose of this study was firstly to develop an investigative protocol for 3D-RA in renal transplanted patients with threatening allograft failure in diagnosing stenosis in the transplanted renal artery; secondly the protocol was evaluated and compared with a modified protocol including reduced contrast medium load. Furthermore, the advantages of the 3D reconstructions compared to the angiographic images were evaluated, likewise if an extended angle of rotation reduced the artifacts in the 3D reconstructions. The two protocols were compared with regard to image quality and acute nephrotoxicity. The accuracy of Doppler ultrasonography and the result of percutaneous transluminal angioplasty (PTA) were also assessed.

3D-RA was consecutively performed in 57 renal transplanted patients with suspicion of renal artery stenosis. A significant stenosis was found in 49% of the patients. The 3D reconstructions profiled 43% of the transplant renal artery stenoses better than the angiographic images. An extended angle of rotation reduced the artifacts. There was no statistical difference regarding image quality between the two protocols, and the renal function was equally affected in both protocols. Doppler ultrasonography sensitivity was 100%; specificity was 48% and positive predictive value 67%. PTA had a technical success rate of 92% and a clinical success rate of 75% after 3 months.

3D-RA is a helpful supplement in cases with complicated vascular anatomy, especially when PTA may be indicated. The 3D reconstructions profile the course of the artery more frequently than the angiographic images and support PTA. The 3D reconstructions are degraded of artifacts. Sampling artifacts can be diminished by increased C-arm rotation and increased number of projections. The distortions caused by beam hardening remain to be solved.

Key words: Kidney, transplantation; renal angiography; renal arteries, stenosis or obstruction; imaging, three-dimensional; artifacts.

Gaute Hagen, Department of Oncology, Radiology and Clinical Immunology, Section of Radiology, Uppsala University Hospital, SE-751 85 UPPSALA, Sweden.
TO MY WIFE ELSE
LIST OF PAPERS

This thesis is based on the following papers:

I. Hagen G, Wadström J, Magnusson A.
   3D Rotational Angiography of Transplanted Kidneys.
   Acta Radiologica 44 (2003), 193-198.

    3D Rotational Angiography of Transplanted Renal Arteries. The Influence of an Extended Angle
    of Rotation on Beam Hardening Artifacts.
    Acta Radiologica (in press).

III. Hagen G, Lindgren PG, Jangland L, Magnusson P, Magnusson A.
     Artifacts in 3D Rotational Angiography. An Experimental Study.
     Submitted.

IV. Hagen G, Wadström J, Magnusson M, Magnusson A.
    Diagnosis and Treatment of Transplant Renal Artery Stenosis with Short-Term Follow-Up.
    Submitted.
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<td>Arteriovenous fistula</td>
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<td>CD</td>
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<td>CTA</td>
<td>CT angiography</td>
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<td>3D</td>
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<td>3D-RA</td>
<td>Three-dimensional rotational angiography</td>
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<td>DSA</td>
<td>Digital subtraction angiography</td>
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<td>LD</td>
<td>Living donor allograft</td>
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<td>MIP</td>
<td>Maximum intensity projection</td>
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<td>MR angiography</td>
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<td>n.a.</td>
<td>not applicable</td>
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<td>PSV</td>
<td>Peak systolic velocity</td>
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INTRODUCTION

Background

Over one million people worldwide have been organ transplanted and some have already survived more than 25 years. More than 40,000 patients are waiting for a kidney in Western Europe (1). In Sweden the first kidney transplantation took place 1964, and till now about 9500 patients have been kidney transplanted. Yearly about 300 kidney transplantsations are performed, where about 30% are from living donors (2). The active waiting list in Sweden for kidney transplantation constitutes 402 patients per December 2003 (3).

Renal transplantation has become a successful treatment for patients with end-stage renal failure. Many patients remain on long-term renal replacement therapy such as haemodialysis or continuous ambulatory peritoneal dialysis due to a lack of suitable donors. Additionally renal transplantation is an expensive procedure, but over time more cost-effective than renal replacement therapy. Furthermore renal replacement therapy maintains a reduced quality of life and higher morbidity and mortality (4-7). Therefore ensuring graft survival is of paramount importance, and early detection of complications is essential.

A substantial part of all patients with kidney transplants develops transplant renal artery stenosis (TRAS), which over time may lead to allograft loss. The incidences varies from 1% to 23% depending on the center, the definition of TRAS, and the intensity of screening performed (8). The detected incidence of TRAS increased from 2.4% to 12.4% at one center with the introduction of colour ultrasonography (9). Several etiologic mechanisms have been proposed for TRAS, including arterial trauma during organ procurement, improper apposition of the donor and recipient vessels with torsion and kinking of the renal artery, suture technique, and atherosclerotic disease in the donor or recipient (8). Chronic rejection is also suggested as a possible cause for TRAS (9), but others (10) have found TRAS equally distributed between living-related and cadaver kidney recipients. Cytomegaloviral infection (11) and cyclosporine a (12) may also play a part in the development of TRAS.

The most common clinical presentations of TRAS are progressive or refractory hypertension and/or allograft dysfunction with increasing creatinine level (7, 8, 10, 13-18). TRAS is often curable, and therefore the recognition of the condition is important to prevent allograft loss. The preferred mode of therapy is percutaneous transluminal angioplasty (PTA) with an immediate technical success rate between 20 and 94% (10, 14, 19-22). The use of metallic stents by TRAS is also widespread (18, 23, 24).

Why a new method?

The visualization of the entire length of the transplant renal artery is crucial in the management of renovascular disease. However, the transplant renal artery is very variable and often tortuous and consequently difficult to image (7, 25, 26).

The gold standard for the diagnosis of renal artery stenosis is angiography and response to treatment is the definitive proof of its significance (25). When conventional digital subtraction angiography (DSA) is used, a number of different projections and contrast medium injections will often be necessary. Consequently there is a possibility for contrast medium induced nephrotoxicity in addition to a relatively high radiation dose. Efforts have been made to replace iodinated contrast media in patients with impaired renal function in native and transplanted kidneys. Especially carbon dioxide has been used (27), but the tortuosity of the artery may lead to break-up of the gas column (16) with poor filling of depend-
ent vessels and both over- and underestimation of stenoses. Additionally there is a risk of vapor-lock-induced renal ischemia (27). A more recent suggestion is to replace iodinated contrast medium for gadolinium (Gd) based contrast medium used in magnetic resonance imaging. This is currently not recommended because the dose needed for radiographic imaging are probably at least as nephrotoxic as the use of iodinated contrast agents (28, 29).

In general minimal or non-invasive imaging methods are preferred because of the rather small risk of complications to the patient, contrary to an arterial catheterization. CT-angiography (CTA) of renal transplant recipients yields valuable information that can be used to guide further therapy (30). However, CTA demands about the same contrast medium load as DSA, and the radiation dose exceeds in most cases a diagnostic DSA. MR-angiography (MRA) provides vascular information in renal transplantation without iodinated contrast, and there is no ionizing radiation (31). Ultrasonography also avoids the problems of iodinated contrast medium and radiation. A comprehensive ultrasound examination of the transplanted kidney includes the different Doppler examinations: duplex Doppler, colour Doppler, and power Doppler. The grey-scale and Doppler-derived information will very often give clinical significance for the handling of the patient with a transplanted kidney (6). Even the use of contrast-enhanced ultrasonography has been shown to be useful in renal transplants (32) without any renal toxicity.

CTA, MRA, and Doppler ultrasonography are diagnostic modalities that can document the transplant renal artery and any actual lesion. These modalities also have the ability to image structures beyond the arteries, but none of them maintain a practical approach to interventional procedures. Conventional DSA has the needed arterial access to percutaneous therapy of vascular diseases, i.e., balloon dilatation, stent placement or embolization, but in transplanted kidneys the number of different projections and contrast medium injections to find a proper projection may be a problem. At this point an alternative method could be appreciated in the investigation of the transplant renal arteries.

In rotational angiography (RA) a series of images are acquired during a continuous rotation of a C-arm around the region of interest (33). By utilizing the angiographic images obtained from the rotational series of the transplant renal arteries to three-dimensional (3D) reconstructions in a dedicated workstation, additional information is achieved, which raises the diagnostic quality and subsequently assures an interventional procedure. Three-dimensional rotational angiography (3D-RA) provides volume rendered 3D images from RA and runs with comparable resolution to that of conventional DSA (34). Advantages and limitations of 3D-RA of transplant renal arteries are investigated in this work.

History of 3D-RA

The rotation technique was proposed by Cornelis et al. (35) already in 1972 but not reported in clinical use until 1983 (36). In 1989 additional DSA to the rotation technique was possible due to improved equipment (37), and eventually in 1997 3D reconstruction of the images from RA was reported (38). 3D-RA has mainly been used for neuroradiological indications (34, 38-40), but the technique should be useful in a number of other indications where the vessels are tortuous, i.e., the arteries of a transplant-ed kidney.
AIMS

Aim for the whole project

The general purpose of this thesis was to investigate the use of three-dimensional rotational angiography (3D-RA) in patients with threatening allograft failure in order to improve the diagnosis of stenosis in the transplanted renal artery and thereby offer a more secure basis for treatment.

The specific aims

- To develop and evaluate an investigative protocol for 3D-RA of the arterial vasculature of the transplant kidney (Paper I).

- To evaluate the advantages of the 3D reconstructions compared to the angiographic images (Paper I and IV).

- To investigate if an extended angle of rotation at rotational angiography of the transplant renal artery could reduce the influence on beam hardening artifacts on 3D reconstructed images. Additionally, two different protocols, with and without arterial occlusion, were compared regarding the image quality and the side effects to the transplanted kidney (Paper II).

- To investigate the artifacts in a vessel phantom and to evaluate how a change of the C-arm rotation, number of projections, and the thresholding parameters influence the distribution of the artifacts in the 3D reconstructions (Paper III).

- To evaluate the accuracy of Doppler ultrasonography in the diagnosis of TRAS, and report the technical and clinical results of the patients that underwent PTA in connection with 3D-RA (Paper IV).
MATERIAL AND METHODS

Patients

All patients examined were consecutive referrals because of suspicion of transplant renal artery stenosis (TRAS) or a stenosis proximal to the anastomosis in the iliac artery. The main reasons for the suspicion of TRAS were increasing creatinine, hypertonia in spite of adequate medicament treatment, bruit over the transplant, biopsy findings indicating ischemia, and suspicion of a stenosis after Doppler ultrasonography examination.

In Paper I 39 patients (18 females and 21 males, mean age 48±12 years (range 23–66 years)) underwent 3D-RA in the time from October 1999 to January 2002. Renal transplantation had been carried out median 6 months (range 0.5–168 months) before the 3D-RA.

In Paper II 12 patients (6 females and 6 males, mean age 48±13 years (range 25–69 years)) underwent 3D-RA with an occlusion technique in the time from August 2002 to February 2003. Renal transplantation had been carried out median 15 months (range 0.5–97 months) before the 3D-RA. These examinations were compared to a control group of 10 patients (7 females and 3 males, mean age 51±11 years (range 26–61 years)), in whom a 3D-RA without occlusion technique had been carried out in a constant way. Eight of the patients in the control group were among the participants in Paper I. The patients had undergone renal transplantation median 8 months (range 0.5–169 months) prior to the 3D-RA. A pilot study of 5 patients preceded the study in Paper II for optimization of the parameters: the angle of the C-arm rotation, the pathway of the balloon occlusion catheter, the amount and the concentration of the contrast medium as well as X-ray delay and injection speed.

Paper IV included totally 57 patients, consisting of the patients examined with 3D-RA from October 1999 to February 2003 with suspicion of TRAS or a stenosis in the iliac artery above the anastomosis. This material consisted of 29 females and 28 males, mean age 48±12 years (range 23–69 years), and the renal transplantation was carried out median 7 months (range 0.5–169 months) prior to the 3D-RA. The causes for renal failure and transplantation were glomerulonephritis (n= 17), diabetes mellitus (n=12), polycystic kidney disease (n=11), IgA nephropathy (n=6), hypertension (n=3), lupus (n=2), tubulointerstitial nephritis (n=1), congenital hydronephrosis (n=1), vesicorenal reflux (n=1), insufficiency after nephrectomy (n=1), and analgetica nephropathy (n=1). One patient (n=1) had both diabetes mellitus and IgA nephropathy.

Thirty-eight patients (67%) received cadaveric kidney allografts (CDs) (34 kidney alone and 4 simultaneous pancreas-kidney transplants) and 19 (33%) living donor allografts (LDs). Forty-six allografts had a single renal artery, 10 had a double renal artery, and 1 had a triple renal artery. The surgical anastomosis was end-to-side to the external iliac artery in 55 patients and end-to-end to the internal iliac artery in 2 patients.

The presentation by referral was one or more of the following: increasing creatinine (n=50), suspicion of TRAS or a stenosis in the iliac artery after Doppler ultrasonography examination (n=44), hypertonia in spite of adequate medicament treatment (n=15), bruit over the transplant (n=11), biopsy findings indicating ischemia (n=9), and claudication in the leg (n=1).
Vessel Phantom

The phantom was a plastic tube with an inner diameter of 5 mm. The tube was filled with contrast medium of the concentration 200 mg I/ml and placed by means of a connector as a closed circle around a plastic cylinder with a diameter of 8.7 cm. The cylinder with the contrast filled tube around was submerged in a water filled plastic bucket which was 23.5 cm broad. The height of the water in the bucket was 8.5 cm and the tube center was at a height of 6 cm during the rotational runs. The plane of the tube circle was parallel to the examination table and perpendicular to the rotation plane (Fig. 1).

Equipment and examination

The rotational angiographies were performed by rotation of a C-arm (Multistar Plus T.O.P., Siemens, Forchheim, Germany). After bringing the region of interest into the isocenter by means of lateral and anteroposterior fluoroscopy a series of images were acquired while the C-arm performed a continuous rotation around the region of interest. The angiographic images were primarily transferred to a separate workstation (Virtuoso, Siemens), where a stack of axial slices was reconstructed. The axial slices in Paper I were then reconstructed at the same workstation with various visualization programs: Maximal Intensity Projection (MIP), Shaded surface Display (SSD), and Volume Rendering Technique (VRT). In Paper II, III, and IV the axial slices were transferred to another workstation (Leonardo, Siemens), in the mean time installed, for the 3D reconstructions.

In Paper I the C-arm rotated 160° with an angulation step of 2.5°. Thus the number of angiographic images constituted 64, and the rotation time was 7 seconds.

In Paper II the C-arm rotated 180° around the region of interest with an angulation step of 2.0° within 9 seconds. In this way 90 angiographic images were created. The control group had a rotation of 160° in 7 seconds and 64 angiographic images, as in Paper I.

Paper III, the experimental study, included the 160° and 180° rotational runs of the other studies, in addition also a run of 180° and 12 seconds. The last setting implied an angulation step of 1.5° and 120 angiographic images.

Paper IV included 160° and 180° rotational runs with 64 angiographic images and rotation time 7 seconds and 90 angiographic images and 9 seconds, respectively.

Catheters and placement

In Paper I the patients got the contrast medium injected through a 4-F catheter (either Straight Aortic Flush, Cordis, Roden, The Netherlands (in 36 patients) or Shepherds Hook, Cordis (in 2 patients)). A 7-F occlusion catheter (Cook, Bjaeverskov, Denmark) with a soft inflatable balloon at the tip was
used in 1 patient. The contrast medium was injected at different sites; with the catheter tip in the aorta just above the bifurcation (n=1), in the proximal common iliac artery (n=23), in the distal common iliac artery (n=10), and in the proximal external iliac artery (n=5).

In Paper II a 5-F balloon occlusion catheter (Boston Scientific – Medi-Tech, Cork, Ireland) was used in all patients in the study group. The puncture was done in the contralateral groin, and the tip of the catheter was placed with crossover technique proximal to the origin of the transplant renal artery. After inflation of the balloon, and thus occlusion of the blood flow, the contrast medium was injected through the catheter. The balloon was inflated approximately 30 seconds. All patients in the control group had a 4-F catheter (Straight Aortic Flush, Cordis) with the tip in the proximal common iliac artery, and the puncture was done in the ipsilateral groin.

In addition to the catheters used in the patients in Paper I and II, Paper IV also included 5 patients with balloon occlusion catheters from the pilot study prior to Paper II.

**Contrast media**

In Paper I the volumes of the injected contrast medium varied between 60 and 135 ml, and different concentrations from 160 to 400 mg I/ml were used. In 20 patients 3D-RA was performed with a dimeric contrast medium (Hexabrix, Guerbet, Paris, France) of different concentrations. In two patients 200 mg I/ml was used, in one patient both 160 and 320 mg I/ml, in another both 200 and 320 mg I/ml were used, and in 16 patients 320 mg I/ml was used. In the remaining 19 patients a monomeric contrast medium (Iomeron 400 mg I/ml, Bracco, Milan, Italy) was used. The flow rate was set to 6–11 ml/s with an X-ray delay of 1.0 second, and the injection lasted for 8 seconds.

In Paper II all the patients got uniformly 24 ml Iomeron 200 mg I/ml, totally 4.8 g iodine. The flow rate was 2 ml/s with an X-ray delay of 3.0 seconds and the injection time was 12 seconds. These were compared to the control group that had 70-75 ml Iomeron 400 mg I/ml, 28.8-30 g iodine. The flow rate was 8-10 ml/s, and the X-ray delay was 1.0 second.

In Paper III the vessel phantom was filled with Iomeron 200 mg I/ml. The concentration of the contrast medium was based on the experience with the same concentration presently used in 3D-RA of transplanted renal arteries when the blood flow is temporarily blocked with an occlusion balloon (41).

Paper IV included both the higher contrast medium dosages used with the conventional catheters as well as the lower ones used with balloon occlusion catheters.

**Radiological assessment and pressure measurement**

In the Papers I, II, and IV the stenoses, either in the transplant renal artery or in the iliac artery, were radiologically assessed and defined by the location; in the common iliac artery, in the external or internal iliac artery, at the anastomosis of the renal artery, and after the anastomosis of the renal artery.

The stenoses were also verified with pressure measurement when possible. The pressure measurements were performed through a 4-F angiographic catheter placed distal to the suspected stenotic area and an introducer placed in the external iliac artery distal to the transplant renal artery anastomosis. After zeroing against the air pressure the system (TruWave, Baxter, Uden, The Netherlands) allowed simultaneous recording of the intra-arterial pressures proximal and distal to the lesion, which could be read out from a multi function monitor (Sirecust SC8000, Siemens). A systolic pressure gradient of 10 mm Hg or more was regarded as significant.

In cases where pressure measurement for different reasons could not be performed, an angiographical
stenosis of more than 50% was accepted as significant.

3D reconstructions
The 3D reconstructions, i.e., maximal intensity projection (MIP), shaded surface display (SSD), and volume rendered technique (VRT), were assessed in Paper I and IV. The angiographic images obtained after the rotational run were compared to the 3D reconstructions at all anastomoses and arteries on both sides of the anastomoses. The examinations, in which the 3D reconstructions gave a better profile of the artery, and thus a more accurate localisation of the anastomoses and possible stenoses compared to the angiographic images, were noted. The stenoses were radiographically defined by the location: in the common iliac artery, in the external or internal iliac artery, at the anastomosis of the renal artery, and after the anastomosis in the renal artery.

Artifacts
Disturbing artifacts experienced in the 3D reconstructions in Paper I were interpreted as beam hardening artifacts. A part of the artery, in the segmental or interlobar arteries and in some cases in the main trunk of the transplanted kidney, was not imaged in the 3D reconstructions in spite of a normal artery in the angiographic images. This insufficient imaging of the artery was distinct where the vessel stretched over a relatively long distance in a slight arch orthogonal to the rotation axis of the C-arm of the equipment. The effect was localized on the inner part of the artery and thus the concave margins were removed while the outermost margins were intact (Fig. 2). The angiographic images showed a normal artery at the same site.

In Paper II the artifacts were evaluated and a comparison was made of 3D reconstructions after 160° and 180° rotational runs. The artifacts were evaluated after a two-point ordinal scale: no artifacts [0] and artifacts [1].

In Paper III the artifacts were evaluated in a vessel phantom. The C-arm rotated with 3 different programs; 160° in 7 seconds with an image every 2.5°; 180° in 9 seconds with an image every 2° and finally 180° in 12 seconds with an image every 1.5°. Thus the number of images was 64, 90, and 120, respectively. In the 3D reconstructions our standard setting for vessels in clinical cases was applied. The settings are expressed in the histogram of grey values of the 3D volume at the Leonardo workstation. The vessel setting implied a tilted ramp with an increase, called window, stretching over 183 arbitrary units of grey values and the centre, called level, at 583 units. Window and level represented the threshold values, expressed in units (U). A colour was applied and the opacity was set to 80% and the brightness to 100%. Then another equal ramp was made with levels set at 500-1300 U with distances of 100 U in the histogram of grey values.

Paper III included also 3 different threshold settings in two clinical cases for the illustration of the varying effect on the 3D image and the influence of the background noise.

Fig. 2.
The concave margin of an artery is partly missing (arrowhead) because of artifacts in the 3D reconstruction.
(Colour print available in the supplement. page 41).
Image quality
The image quality was assessed in Paper I, II, and IV. In Paper I and IV the examinations in which the 3D reconstructions gave a better profile of the anastomosis and the stenosis compared to the angiographic images were noted.

In Paper II the 3D reconstruction and angiographic image quality of the two protocols, with and without arterial occlusion, were assessed. The image quality of the 3D reconstructions of the arteries were evaluated by an experienced radiologist according to a four-point ordinal scale; poor [1] defined as nondiagnostic, fair [2] defined as discontinuous arteries, good [3] defined as continuous but not smooth arteries, and excellent [4] defined as continuous and smooth arteries. Two levels of the transplant renal arteries were assessed: firstly the anastomosis defined within 5 mm from the ostium, and secondly the main trunk of the renal transplant artery including the branching into the segmental arteries.

The angiographic images of the two protocols in Paper II were evaluated by another experienced and independent radiologist. The image quality was also evaluated according to a four-point ordinal scale: poor [1], fair [2], good [3], and excellent [4], where poor was defined as nondiagnostic. The same two levels as in the 3D reconstructions of the transplant renal artery were evaluated.

Acute nephrotoxicity
The acute nephrotoxicity of contrast media was investigated in Paper II. The creatinine levels of the patients in both study and control groups were noted within 0 to 7 days before and 1 to 5 days after the 3D-RA to depict any differences in the renal function between the two protocols, with and without arterial occlusion, after administration of the contrast medium. A significant renal influence was defined as a creatinine level increase of at least 25% or an increase of 44 µmol/l or more (42, 43).

Doppler ultrasonography
In Paper IV the accuracy of Doppler ultrasonography in the diagnosis of TRAS was evaluated. A significant stenosis was suspected when the peak systolic velocity (PSV) was 2.5 m/s or more. The Doppler angle was 60° or less.

Technical and clinical success of PTA
Paper IV included all patients examined with 3D-RA and was designed to evaluate the effect on renal function after PTA and stent placement. The creatinine levels after 1 and 3 months were noted, likewise the alterations in hypertensive drugs before and 1 and 3 months after the 3D-RA were assessed. In the cases where the pressure measurement for different reasons could not be performed, an angiographical residual stenosis of less than 50% was accepted as an immediate technical success. Short term clinical success was defined as more than 0.3 mg per deciliter (27 µmol per liter) reduction in serum creatinine, and/or a reduction in the number of antihypertensive drugs.

Also, the complications in connection with 3D-RA and PTA were assessed.

Statistics
Data are presented as the median or mean ± 1 SD when applicable in addition to range. Statistical significance is accepted within 95% confidence limits. In Paper II the Mann-Whitney test is used by analyzing the quality of the angiographic images and the 3D reconstructions. In Paper IV the creatinine level before and after 3D-RA are compared using a paired t-test. Patients serve as their own controls, before and after angioplasty. To compare the time from transplantation to 3D-RA between the patients with and without TRAS the Wilcoxon rank-sum test is used. A paired t-test is applied for the calculation of the reduction of the number of the antihypertensive drugs. All statistical analysis is performed with S-Plus version 6.1.
RESULTS

Investigative protocol
In Paper I it was important to achieve a uniform concentration of contrast medium in all 64 projections. In the beginning of the study the contrast medium was injected with a low flow, and the tip of the catheter was placed close to the transplant renal artery. With this position of the catheter the pulsating blood could cause disturbing variations in contrast density in the angiographic projections achieved during the rotation of the C-arm. Different sites of contrast medium injection were performed, and the variations of the contrast density were acceptable when the tip of the catheter was placed in the proximal part of the common iliac artery, yet without spill-over of contrast medium to the contralateral iliac artery. Additionally the injection speed had a considerable influence on the contrast density variations, where 8–10 ml/s gave relatively uniform concentration.

In Paper II a different investigative protocol was evaluated to reduce the artifacts and the contrast load experienced in Paper I. The different parameters of the examination were constant in all patients of the study group in Paper II, i.e., the rotation angle of the C-arm, the balloon occlusion catheter placement, amount and concentration of the contrast medium, as well as the flow rate and the X-ray delay. The parameters were based on the results from Paper I and the pilot study of 5 patients prior to Paper II. In the control group, in which conventional catheters were used, the above mentioned parameters had minor variations.

Benefit from the 3D reconstructions
The use of 3D reconstructions gave the possibility of choosing any angulation to the arteries, and thus a better profile of the stenosis compared to the angiographic images could be demonstrated. In Paper I the 3D reconstructions provided a contribution in terms of a better profile of the stenosis, and thus clinically important, in 10 (26%) of the patients examined (Fig. 3). One patient had an aneurysm that only could be seen in the 3D reconstructions.

Fig. 3.
Clinical importance of 3D reconstruction. a) The angiographic image of the rotational angiography (enhanced area) shows an apparently mild stenosis at the origin of the transplant renal artery. b) The 3D reconstruction from the same angle gives the same impression (arrow), but after rotation of the 3D volume and view from below (c) the true stenosis is depicted (arrow). The systolic pressure gradient was 35 mm Hg.
In Paper IV, which represented all the patients examined with 3D-RA, the 3D reconstructions made a better profile of the stenosis in 12 (43%) out of 28 TRAS, 2 of them in the same patient. This applied also for 1 of the 3 stenoses in the common iliac artery. Fig. 4 shows another example of the benefit of 3D reconstructions.

Artifacts in the 3D reconstructions of the transplant renal arteries
In Paper I beam hardening artifacts were a problem that was not possible to solve neither by changing the contrast medium concentration/amount nor the position of the angiographic catheter. These artifacts occurred in most of the examinations and had varying effects on the quality of the images.

In Paper II the artifacts clearly became less frequent by increasing the C-arm rotation from 160 to 180°, creating 64 respectively 90 angiographic images. The artifacts in the 3D reconstructions appeared in 4 (36%) of the 11 patients in the study group, and in the control group 100% had the artifacts. The artifacts were all located more peripheral in the renal artery tree and did not affect the anastomosis.

In the clinical cases of Paper III the artifacts were apparent in the higher threshold levels. The distance in the histogram of grey values between the disappearance of the artifacts and the appearance of background noise was very narrow or even overlapping in one clinical case with a 160° rotational run, and it was not possible to make a sensible 3D reconstruction without artifacts (Fig. 5). In the other case a 180° rotational run was applied and by the lowering of the level the arteries were imaged with clean margins. Further lowering caused background noise and blurring of the arteries (Fig. 6).

Artifacts in the 3D reconstructions of the vessel phantom
All artifacts were localized in the most cranial positioned part of the circular vessel phantom. At this part the vessel phantom had a longer path parallel to the rotation plane.

Also the appearance and extensiveness of the artifact were characterized by a lack of filling on the concave margin of the vessel phantom curvature, while the outermost margin was intact in the lower threshold settings.
Artifacts in a patient with a transplanted kidney after a 160°/64 images rotational run (VRT, window 183 U, different levels). a) A high level (770 U) implies pronounced artifacts. b) Even with the optimal level (610 U) the artifacts degrade the VRT reconstruction. c) By lowering the level (540 U) the background noise is increasingly disturbing.

(Colour print available in the supplement. page 42).

Fig. 6.
Artifacts in a patient with a transplanted kidney after a 180°/90 images rotational run (VRT, window 183 U, different levels). a) A high level (880 U) implies pronounced artifacts. b) The optimal level (670 U) shows a good signal-to-noise ratio and smooth arteries are imaged. c) The background noise appears by further lowering of the level (490 U).

(Colour print available in the supplement. page 42).
With the use of our standard vessel setting at the workstation the artifacts were apparent, but they decreased with increasing rotation angle and projections. By applying a gradual higher level the extensiveness of the artifacts increased. Beyond a level of 800 U the 3D reconstructions were rather similar with reduced visualization of the vessel phantom margins and thus not appropriate for diagnostic purposes. The artifacts could not be completely removed by means of threshold settings, and at the lowest levels the background noise blurred the concave margins of the vessel phantom.

The artifacts were distinct in the 3D reconstruction from the 160° rotational run. By increasing the angle of rotation to 180° and 90 images the artifact diminished, and further diminution was achieved by 180° rotation angle and 120 images (Fig. 7). Similar to the threshold settings it was not possible to remove the artifacts completely by means of the extent of the C-arm rotation or the amount of projections. However, with the combination of the most optimal level and the most extended rotation, an applicable signal-to-noise ratio in the 3D reconstruction was achieved.

**Image quality**

The image quality was assessed independently from the artifacts in Paper II. In the 3D reconstructions there was no statistical difference in the image quality between the two protocols, with and without arterial occlusion, applied. The qualitative analysis is described in Fig. 8. The \( P \)-values were 0.85 and 0.18, respectively, for the two levels evaluated.

There was also no statistical significant difference between the angiographic image quality using either a balloon occlusion catheter or a conventional catheter. This applied to both levels assessed: the anastomosis and the main trunk with the dividing area into the segmental arteries. Fig. 9 describes the qualitative analysis of the angiographic images in both groups and at both levels. The \( P \)-values were 0.35 for level 1 and 0.44 for level 2.

**Renal function**

Based on changes in creatinine level before and after 3D-RA there was no statistical difference between the examinations with and without arterial occlusion in Paper II.

Out of 24 patients undergoing PTA (Paper IV) a significant reduction of creatinine was seen in 2 patients (8%) after 1 month and in 8 patients (33%) after 3 months.

**Accuracy of Doppler ultrasonography**

Fifty-five of the 57 patients in Paper IV were examined with Doppler ultrasonography before the 3D-RA. Two patients without Doppler ultrasonography did not have any stenosis. After Doppler ultrasonography 42 patients (76%) had a suspected stenosis; 35 patients with TRAS, 5 patients with iliac artery stenoses, and 2 patients with both TRAS and iliac artery stenosis. There were no false-negative Doppler ultrasonography, but 14 patients were false-positive, all TRAS. Thus the sensitivity of Doppler ultrasonography was 100%. The specificity was 48% and the positive predictive value was 67%.

**Technical success of PTA**

The immediate technical success of PTA for TRAS was 22 (92%) out of 24 stenoses. PTA did not succeed in 2 of the stenoses; one at the anastomosis and another after the anastomosis. There was no relation between stenoses at or after the anastomosis and the technical success rate. The four stenoses treated in the iliac artery were all technically successful (Table).

**Clinical success of PTA**

The clinical success after 1 month was 14 (58%) out of 24 patients and increased to 18 patients (75%) after 3 months (Table). Twelve patients had a reduc-
VRT reconstructions of the vessel phantom show the influence of the artifact with increasing rotation angle/number of images. The left column of images illustrates the 160°/64 images rotational run, the middle column the 180°/90 images rotational run, and the right column the 180°/120 images rotational run. The level is at 500 U at the top row, followed by 600 U, 700 U, and 800 U, respectively. The window is 183 U in all images. (Colour print available in the supplement. page 43).
Fig. 8.
The distribution of the quality of the 3D reconstructions. White bars represent patients in the study group at level 1 (at the anastomosis), light grey bars are controls at level 1, dark grey bars are patients in the study group at level 2 (after the anastomosis) and black bars are controls at level 2.
The numbers on the x-axis: 1 = poor, 2 = fair, 3 = good, and 4 = excellent.

Fig. 9.
The distribution of the quality of the angiographic images. White bars represent patients in the study group at level 1 (at the anastomosis), light grey bars are controls at level 1, dark grey bars are patients in the study group at level 2 (after the anastomosis) and black bars are controls at level 2.
The numbers on the x-axis: 1 = poor, 2 = fair, 3 = good, and 4 = excellent.
<table>
<thead>
<tr>
<th>Sex</th>
<th>Age</th>
<th>Level of stenosis</th>
<th>Technical result</th>
<th>Result 1 month</th>
<th>Result 3 months</th>
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<tr>
<td></td>
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<td>Reduced Creatinine</td>
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</tbody>
</table>

Table.
Immediate technical result of PTA and clinical results after 1 and 3 months in 24 patients with transplant renal artery stenosis and iliac artery stenosis.
tion of antihypertensive drugs after 1 month, 11 patients after 3 months. The number of the antihypertensive drugs used before PTA was significantly reduced three months after PTA ($P=0.00168$).

**Complications**

Complications occurred in 11 (18%) out of the 57 patients that underwent 3D-RA, of whom two patients also had PTA. One PTA patient developed a pseudoaneurysm in the groin which was embolized, and the other one had a haematoma in the groin and needed blood transfusion. In one patient the guide wire made a perforation distal in the aorta necessitating an emergency operation. This patient had an extensive atherosclerotic disease and was operated twice, but developed pancreatitis and finally multiorgan failure, and died 7 months later. Two patients had intimal dissection; in one patient the dissection occluded a polar artery which was operated acutely with a bypass; the other patient, with diabetes mellitus, got a heart infarction after the 3D-RA. Additional complications were groin haematoma ($n=3$) of which 1 was operated, groin pseudoaneurysm ($n=1$) which was embolized, and loss of allograft function ($n=1$). The patient with loss of the allograft function was pre-uremic at the time of the examination, and after the 3D-RA the kidney lost the residual function. He had a relatively mild stenosis at the anastomosis (systolic pressure gradient 13 mmHg).
GENERAL DISCUSSION

There are many techniques how to overcome the problem of superimposing vessels in contrast examinations. For the diagnosis of a stenosis a minimal or non-invasive procedure as CTA, MRA or Doppler ultrasonography is preferred. CTA can be carried out with about the same contrast load applied intravenously as 3D-RA, and MRA and Doppler ultrasonography can be carried out without nephrotoxic contrast medium. Additionally these modalities have the ability to image structures beyond the arteries. However, only traditional DSA has offered the possibility of an immediate intra-arterial intervention, but this technique may require several projections and multiple injections of contrast medium. In patients with transplanted kidneys the vascular anatomy is often complicated with a tortuous artery, which runs in the sagittal plane. A main goal is to keep the contrast load as low as possible especially in patients with decreased renal function. 3D-RA with the use of conventional angiographic catheters will in a number of cases reduce the contrast load compared to traditional DSA. In patients where interventional procedures are necessary, the contrast reduction will be quite marginal because the rotational run is only a limited part of the examination which helps to find the best projection for further workout.

There is a general aim to lower the radiation dose. By 3D-RA the whole vessel is depicted in one run, which also facilitates the best projection for further angiography and intervention at the same time. Compared with conventional single plane DSA rotational angiography implies an increased radiation dose from 1.3-fold (44) to 2.6 (45). With increasing number of single plane injections the radiation dose increases accordingly, and this means that rotational angiography in many cases will reduce the total radiation dose (33).

It is widely accepted that pressure measurements are superior to angiography in documenting a stenosis (46, 47). The results of pressure measurements in the aortoiliac segment and the peripheral vascular system have been transferred to the renal artery (48), but there is no consensus regarding the cut-off level in transplanted renal arteries (49). Our cut-off level at a peak systolic gradient at 10 mmHg was quite low, but in spite of this the immediate technical success was 92%, which is comparable with others (10, 14, 19, 21, 50) who only used the angiographic result as comparison.

The 3D reconstructions gives valuable information in addition to the angiographic images (9, 39, 49). A good projection for further angiographic investigation can be chosen immediately after the axial rotational run of the C-arm of the equipment, but it is limited to rotation across the z-axis. However, sometimes it is not possible to profile a vessel in the desired region without angling the observer view cranially or caudally because of overlying structures or other vessels. The 3D reconstructions solve this problem to a substantial grade as the optimal projection can be found, but it is not always possible to utilize this projection, as it would require the C-arm to be positioned within the patient’s body or within the examination table. The transplant renal artery has often a tortuous course (7, 49), and we found the 3D reconstructions helpful to profile the transplant renal artery anastomosis and the course of the artery, and in this way supportive and confirmative for the diagnosis of a stenosis.

3D-RA includes a relatively high ground artifact level caused by the low number of projections (51), which not only includes the equipment used in this study, but can also be seen in examinations performed on equipment from other manufacturers. The 180° rotational run is not quite sufficient for a reconstruction. Increasing the number of projections will primarily decrease the ground artifact level (51). However, this means that the examination re-
quires a higher radiation dose; the contrast load will
in most cases increase as a contrast filling of the ves-
sels is necessary during the whole rotational run, and
the procedure will be more time consuming. A bet-
ter approach may thus be to reduce the artifacts by
additional post processing methods, but at present
eliminating the artifact like that in our study is not
solved.

The beam hardening artifact is most distinct when
the beam passes higher attenuating objects with long
horizontal paths in the tissue as bone or contrast
filled vessels. The sampling artifact, that in our study
amplifies the beam hardening artifact, is character-
ized by fine streaks emanating from high frequen-
cy interfaces, as at the border between the contrast
filled vessel and surrounding tissue. However, in the
reconstruction of the 3D images the beam harden-
ing artifact, together with the sampling artifact, ap-
ppears as a change in tissue composition at the borders
of the contrast filled vessel in areas where the vessel is
parallel to the original X-ray beam. As a result of this
calculation error an artifact arise as a shadow with
lower grey scale values beneath the contrast filled
vessel, blurring also the edges of the vessel.

The majority of the studies that have been done
with vessel phantoms and 3D-RA have been re-
lated to aneurysms of cranial arteries (52-56). The
cranial arteries do not have long orthogonal paths,
and thus the problems we experienced with beam
hardening artifacts in the arteries of the trans-
planted kidney (41, 49) do not exist to the same ex-
tent on the arteries in the basis of the skull.

The C-arm of the equipment is mechanically un-
stable and during the acceleration of the C-arm tran-
sient vibration occurs which may result in blurring
of the vessel edge (54, 57). This blurring affects how-
ever both edges of a vessel, and as the artifact in our
study was distinct on the concave side of the vessel, it
is not assumed that the instability of the C-arm con-
tributed significantly to this artifact.

In spite of the considerable reduction of the con-
trast load in Paper II no quality differences of the 3D
reconstructions could be shown in the two groups.
However, in our opinion the 3D reconstructions
were better with the extended rotation of the C-arm.
One explanation for this is the small number of the
two groups, but another is that the image quality
was measured in two relatively proximal levels: first-
ly near the anastomosis, secondly the main trunk
with the dividing area into the segmental arteries.
The peripheral zone was not assessed as to image
quality. However, the beam hardening artifacts ap-
peared more peripheral where the vessels stretched
over a relatively long distance in the axial plane par-
allel to the X-rays. As the beam hardening artifacts
were clearly less apparent in the study group, which
probably also was attributable to the increased angle
of rotation, the image quality was surely better more
peripheral in the transplanted kidney when the oc-
clusion technique was used.

There were neither any quality differences of the
angiographic images in the examinations with and
without arterial occlusion. However, the contrast
filled area of arteries was less with occlusion of the ex-
ternal iliac artery. The part of the external iliac artery
proximal to the occlusion balloon was not contrast
filled, likewise partly the artery distal to the trans-
plant renal artery anastomosis because the contrast
medium was shunted into the kidney (Fig. 10).

The use of a balloon occlusion catheter in Paper
II allowed a considerable reduction of the contrast
load. It could, however, be assumed that the occlu-
sion of the circulation of the transplanted kidney and
the static contrast filling of the arteries for approxi-
mately 30 seconds might be even more nephrotoxic
than contrast medium in circulation in spite of only
half the concentration being used. There was no sta-
tistical difference in the creatinine levels in the two
groups investigated but the numbers of the groups
were small. In some of the patients the blood sam-
pling was carried out the day after the 3D-RA, which
was the day they were dismissed from the hospital,
and this may be too early to indicate any affection on the renal function. The increase in serum creatinine is characteristic of contrast medium induced nephropathy. The nephrotoxic effect of the iodinated contrast media starts shortly after the administration, but the increase in serum creatinine often peaks after 3 to 4 days. It is therefore possible that the occurrence of contrast media induced nephrotoxicity is underestimated if the serum creatinine is monitored too early (58, 59). However, a recent study (60) demonstrated that any adverse renal outcome is unlikely to incur with a rise in the creatinine level less than 44 µmol/l 24 hours after contrast exposure.

Doppler ultrasonography is useful for early detection of TRAS (7, 9), and Doppler ultrasonography is the most frequently used technique to examine the vascular stalk of the renal transplant (6). The method has been reported to have a sensitivity of 87% to 94% and a specificity of 75% to 100%, but a positive predictive value as low as 56% in the diagnosis of TRAS (13, 61, 62). Rendering the transplanted kidney is ideal for Doppler ultrasonography because the transplanted kidney has a superficial position in the iliac fossa. Although the orientation of the transplanted kidney is variable, perpendicular images can normally be obtained. However, the transplant renal artery is a difficult vessel to study as it is extremely tortuous (7, 25, 26), and the normal PSV range up to 2.5 m/s (7).

Because of the accessibility, non-invasiveness, and high sensitivity of Doppler ultrasonography all but two patients in our study had undergone the examination before referral to 3D-RA. Our Doppler ultrasonography material had a very high sensitivity, but the positive predictive value and especially the specificity was very low underlining that an angio-
graphic confirmation is still required. Kinks in the transplant renal artery increase the PSV, allowing for stenosis misinterpretation. Additionally, Doppler ultrasonography is generally very operator dependent.

Similar to pressure measurements in transplanted renal arteries there is a lack of consensus in the definition of clinical success following PTA of transplanted renal arteries. Several authors have based the definition of clinical success on normalization of hypertension or reduction in the use of antihypertensive drugs (10, 14, 15, 19-21, 50, 63) and/or a significant improvement of kidney function. There is, however, no consensus on the definition of a significant improvement of kidney function. In the field of transplantation numerous studies have dealt with the issue of prevention and treatment of allograft rejection. There has consequently been a need to make a definition of what should be considered as a significant reduction of kidney function. At a consensus conference it was proposed that a significant reduction of kidney function should be defined as an increase in serum creatinine of 0.3-0.4 mg/dl (64). We used a corresponding decrease in serum creatinine as the definition for clinical success, but others (10, 14) have used a serum creatinine reduction of 15% to define clinical success without any further elucidation. Although serum creatinine correlates imperfectly with the renal function, its choice is imposed by its routine and standardized use. The correlation of absolute serum creatinine levels with more specific measurements of the renal function, such as creatinine clearance, is low in renal transplantation (65). However, serial serum creatinine levels in any given patient offer a good assessment of changes in renal function (66).

A comparison of the results of interventions is limited by the varying definitions employed for success (8), and a general definition of clinical success after PTA of transplanted renal arteries would thus be appreciated. However, the variability of the definitions is also an indication of the difficulties in handling the effect of any treatment of transplanted kidneys because of the multiple causal connections for decreased renal function including surgical technique, infections, dehydration, recurrence of the disease, vascular, non-vascular, immunological, and medication complications. Consequently, the longer the time lapsed since an intervention, the more difficult will it be to relate the outcome to this particular intervention or treatment.

Our short-time clinical success rate increased from 58% after one month to 75% after three months. The success rate seems to be at least as satisfactory as others (10, 14, 19, 21, 61), resulting in a significant initial improvement or cure average of 73% (67). The reasons for the increasing success rate from one to three months after PTA may have connection with the multifactorial effects on transplanted kidneys. Others (18) have also showed a gradual decrease of the creatinine level after PTA.

Although the total number of complications in this study was considerable, the PTA complications were few, and among them there were no arterial dissection, rupture or thrombosis. According to other studies (15, 19, 21) complications in connection with PTA may occur in up to 10% of the cases, including haematoma at the femoral artery puncture site and intimal flaps.

Future outlook
The use of 3D-RA was established some years ago in the field of neuroradiology. It has not yet been widely spread into other fields, but the computer development is tremendous and the 3D-RA technique is likely to enforce whenever interventional radiology is needed. The technique provides a unique survey of the anatomy and makes an immediate intervention possible. The intervention is made more secure in situations where superimposed vessels are disturbing. In addition to a helpful tool in the handling of transplanted kidneys, the 3D-RA technique is generally useful in tortuous vessels. The assessment of the
coronary arteries is a huge potential for 3D-RA, the utilization of which is already in progress. The technique can also be utilized in structures outside the blood vessels such as the collecting system of the kidneys and the biliary tree in combination with percutaneous transhepatic choleography (PTC). Moreover, 3D-RA can be helpful in the evaluation of orthopedic conditions such as complicated fractures, may be in combination with embolization, and evaluation of metallic implants, which is difficult with CT and MRI because of the resulting artifacts. Even the detection of breast cancer may take advantage of the 3D-RA technique.

3D-RA has the outlook for the benefit of safety, outcome, and costs.
CONCLUSIONS

• RA of transplanted kidneys represents a promising method in imaging of the renal artery when an interventional procedure was expected. The combination with 3D reconstructions has opened up new possibilities, and to obtain the best images a high concentration contrast medium should be injected through a catheter with the tip placed in the proximal common iliac artery. The recommended contrast medium volume is 70–75 ml at a flow rate of 8–10 ml/s.

• The 3D reconstructions made it possible to profile the transplant renal artery anastomosis and stenoses in the course of the artery more frequently than the angiographic images, and thus the 3D reconstructions were supportive for PTA.

• 3D-RA with extended C-arm rotation reduced the influence of beam hardening artifacts. The angiographic images and the 3D reconstructions were not reduced in quality in spite of the reduced contrast medium load. There was no difference in patient outcome between the two protocols, with and without arterial occlusion.

• The quality of the 3D reconstructions from RA was degraded by beam hardening artifacts and sampling artifacts. The sampling artifacts were diminished by an increased rotation angle and an increased number of projections. The distortions in the 3D reconstructions caused by beam hardening remain to be solved. The threshold values also had a considerable influence on the 3D reconstructions.

• 3D-RA was superior to Doppler ultrasonography in diagnosing TRAS. The technical and clinical success rates for the patients with 3D-RA and PTA were satisfactory.
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SUMMARY IN SWEDISH

TREDIMENSIONELL ROTATIONSANGIOGRAFI AV TRANSPLANTERADE NJURARTÄRER - EN KLINISK OCH EXPERIMENTELL STUDIE.

Tredimensionell rotationsangiografi (3D-RA) är en etablerad metod inom den interventionella neuroradiologin för kartläggning av hjärnans blodkärn. Metoden har emellertid också en stor potential inom andra organområden med komplicerad kärnanatomii. Syftet med denna studie var:

- att utveckla ett protokoll för 3D-RA undersökning av transplanterade njurartärer hos patienter med hotande transplantatsvikt och misstanke om njurartärstenos,
- att undersöka om 3D rekonstruktioner tillför någon kliniskt viktig information jämfört med angiografibilder,
- att experimentellt studera artefakter i de rekonstruerade bilderna samt undersöka om och hur artefakterna kan minskas,
- att undersöka tillförlitligheten för ultraljud Doppler att påvisa artärstenoser i den transplanterade njurartären,
- att studera resulterna av ballongvidgning (PTA) av påvisade artärstenoser.


I den experimentella delen av studien studerades hur olika rotationsvinklar, antal projektioner och inställning av tröskelvärden för gråskalan inverkade på förekomsten av artefakter.

Den ökade rotationsvinkeln, från 160° till 180°, minskade artefakterna. Hos 100 % av patienterna, som undersöks med 160°, föreläg artefakter medan endast 36 % som undersöks med 180° rotation upvisade artefakter. Det föreläg inte någon skillnad i bildkvalitet mellan de båda protokollen och inte heller någon skillnad i påverkan på njurfunktionen.

Hos 49 % av de undersöka patienterna påvisades en signifikant stenos. Sensitiviteten för ultraljud Doppler var 100 % och specificiteten var 48 %. Hos 43 % av patienterna med signifikant stenos gav 3D rekonstruktionerna bättre diagnostisk information än angiografibilderna. Ballongvidgningen var tekniskt lyckad hos 92 % av patienterna med signifikant stenos, efter 3 månader var 75 % kliniskt förbättrade.
Experimentellt påvisades artefakterna inom den del av kärlfantomet som förlöpte parallellt med rotationsplanet. Artefakterna ökade i utbredning med ökande tröskelvärden för gråskalan. Artefakterna minskade i storlek när rotationsvinkeln och antalet projektioner ökade.

REFERENCES

2. www.organdonation.a.se.


COLOUR SUPPLEMENT

Colour figures from thesis and from papers originally in colour.

Thesis Fig. 1 and Paper III - Fig. 1.

Thesis Fig. 2 and Paper II - Fig. 2.
Thesis Fig. 4 and Paper IV - Fig. 2.

Thesis Fig. 5 and Paper III - Fig. 4.

Thesis Fig. 6 and Paper III - Fig. 5.
3D ROTATIONAL ANGIOGRAPHY OF TRANSPLANTED RENAL ARTERIES

Thesis Fig. 7 and Paper III - Fig. 3.
Thesis Fig. 10 and Paper II - Fig. 5.

Paper I - Fig. 1.
3D ROTATIONAL ANGIOGRAPHY OF TRANSPLANTED RENAL ARTERIES

Paper I - Fig. 2.

Paper I - Fig. 4.
Paper II - Fig 1.

Paper III - Fig 2.