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MRI with MR Angiography in Endovascular Repair of Abdominal Aortic Aneurysms

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Abstract

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This study has shown that for MR-compatible stent-grafts, MRI/CE MRA could be the method of choice for follow-up of endovascularly repaired AAA. For patients with pre-existing renal insufficiency MRI/CE MRA should be the method of choice.

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Lena Engellau

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Lena Engellau

Department of Radiology, Lund University, 2002

MRI with MR Angiography in Endovascular Repair of Abdominal Aortic Aneurysms

Lena Engellau
Leg. läkare

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A 1.5 T scanner was used for all examinations. In this prospective study 26 consecutive patients were included. Follow-up was performed between February 1995 and May 2002 (median follow-up; 36 months, range 8-84 months). In Paper I, we assessed the value of MRI/CE MRA as follow-up method. MRI/CE MRA provided the relevant information. MRI was the sole method demonstrating intramural thrombus organization and vertebral body infarction. In Paper II, we evaluated MR safety; ferromagnetism and heating of a nitinol stent-graft. Image artefacts were also evaluated on MRI/CE MRA and CT. In addition, an extended MR protocol including velocity mapping was assessed. MRI in a 1.5 T system may be performed safely in patients with the nitinol stent-graft (Vanguard). MRI/CE MRA provided diagnostic image information with only minor metal artefacts. Image evaluation on CT can be disturbed at the graft limb junction and graft bifurcation by the beam hardening artefacts. MR velocity mapping did not provide additional information. In Paper III, we compared measurements for stent-graft planning. MRI/CE MRA was compared with DSA and CT. The MRA post processing techniques MIP and VRT were also compared. The length measurements obtained with MRA-MIP were significantly shorter, but probably more correct, than those obtained with DSA. The diameter measurements obtained with MRI/CE MRA were more variable. Improvements of the MRA technique and a standardized determination of the vessel boundaries are needed for more reliable diameter measurements. In Paper IV, we compared costs of follow-up with MRI/CE MRA with costs of follow-up with CT with DSA, or CTA. The cost analysis included a risk analysis of contrast media induced nephropathy. MRI/CE MRA can be cost-effective for follow-up depending on the risk of contrast media induced nephropathy for CT with DSA, or CTA. In Paper V, we presented mid-term results with the Stentor and Vanguard stent-grafts assessed with MRI/CE MRA. Complications and secondary interventions were common. Long-term follow-up is mandatory. This study has shown that for MR-compatible stent-grafts, MRI/CE MRA could be the method of choice for follow-up of endovascularly repaired AAA. For patients with pre-existing renal insufficiency MRI/CE MRA should be the method of choice.

Key words: Aneurysm, aortic, Endovascular repair, Stent-graft, MR imaging, MR angiography, MR imaging safety, Artefacts, MR velocity mapping, Cost analysis, Contrast media complications.

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V   Engellau L, Albrechtsson U, Norgren L and Larsson E-M.
     Mid-term results after endovascular repair of abdominal aortic aneurysms with the Stentor and Vanguard stent-grafts: Follow-up with magnetic resonance imaging with MR angiography.
     Submitted 2002.

Abbreviations

AAA	abdominal aortic aneurysms		**MRA**	magnetic resonance angiography
BW	band width		**MRI**	magnetic resonance imaging
CE	contrast enhanced		**NITINOL**	nickel-titanium alloy
CMIN	contrast media induced nephropathy		**PC**	phase contrast
COR	coronal		**ROI**	region of interest
CT	computed tomography		**SAG**	sagittal
CTA	computed tomography angiography		**SAR**	specific absorbed ratio
2D	two-dimensional		**SE**	spin echo
3D	three-dimensional		**SNR**	signal to noise ratio
DSA	digital subtracted angiography		**T**	Tesla
EPI	echo-planar imaging		**T1**	characteristic time of longitudinal or spin-lattice relaxation
ETL	echo train length			
EUROSTAR	European collaborators on stent-graft techniques		**T2**	characteristic time of transverse or spin-spin relaxation
FA	flip angle		**TE**	echo time
FLASH	fast low-angle shot		**TOF**	time of flight
FOV	field of view		**TR**	repetition time
Gd	gadolinium based contrast agent		**TRA**	transverse
GRE	gradient refocused echo		**TSE**	turbo spin echo
i.v.	intravenous		**VENC**	velocity encoding
MIP	maximum intensity projections		**VRT**	volume rendering technique
MPR	multiplanar reconstruction			

Populärvetenskaplig sammanfattning

Bakgrund

Sedan Wilhelm Conrad Röntgen upptäckte röntgen-strålar 1896 utvecklades den diagnostiska röntgen-tekniken snabbt. Under första hälften av 1900-talet var användningen av joniserande strålning i form av röntgenstrålar den enda princip med vilken den allt mer tekniskt avancerade röntgendiagnostiken bedrevs. För att åskådliggöra blodkärl använder sig konventionell röntgenteknik av kontrastmedel som injiceras i blodbanan. Dessa kontrastmedel är jodhaltiga, och har nackdelen att de dels kan vara allergiframkallande, dels kan ha en påverkan på njurfunktionen, framför allt hos patienter med redan nedsatt njurfunktion. Användningen av joniserande strålning vid kärlröntgen (Angiografi eller DSA) och skiktröntgen (CT) medför en inte försumbar stråldos till patienter. Det är en allmän målsättning att reducera den medicinska strålningen till patienter när det är möjligt. Vid angiografi sker en kateterinläggning i en pulsåder via ett instick i ljumsken. Denna undersökning är således invasiv och har en viss risk för komplikationer, speciellt hos kärl-sjuka patienter.

Magnetisk resonanstomografi

Magnetisk resonanstomografi (MR), ofta benämnd magnetkamera, är en metod som används för att visua-lisera kroppens anatomi och funktion. MR tekniken började användas för kliniskt bruk under början av 1980-talet. MR utnyttjar inte joniserande strålning utan bygger istället på att vissa atomer har ett mag-netiskt moment, som gör att de orienterar sig på ett visst sätt i ett yttre pålagt magnetfält. Väteatomerna, som är en av byggstenarna i vatten, har en kärna (pro-tonen) som är speciellt lämpad att studera med denna metod. När kroppens vävnad utsätts för ett externt statiskt magnetfält orienterar sig de enskilda vätekär-norna parallellt med det externa magnetfältet. Med hjälp av en för vätekärnan speciellt anpassad radiovåg utsänd av en så kallad sändarspole i magnetkameran, kan väteprotonernas exciteras vilket makroskopiskt sett kan uppfattas som att deras orientering tippas till ett plan vinkelrätt mot det externa magnetfältet. Då radiovågen upphör återgår väteprotonerna till att vara riktade parallellt med det externa magnetfältet och en liten mängd energi avges, vilken kan detekteras som en signal genom induktion i en mottagarspole. Beroende på antalet väteatomer som finns i de olika vävnaderna i kroppen, så kommer denna signal att bli vävnadsspeci-fik. Den detekterade signalen kan sedan rekonstrueras till två- eller tredimensionella bilder som återger vävna-dernas anatomi.

Vid blodkärlundersökning med MR-teknik kan kontrast förstärkt MR-angiografi (CE MRA) använ-das. Vid CE MRA ökas kontrasten från blodet med hjälp av det paramagnetiska grundämnet gadolinium. Det gadoliniumbaserade kontrastmedlet, som injiceras i en ven i armen, är oskadligt för njurarna och är heller inte allergiframkallande. Vid CE MRA detekteras signalerna från blodet tredimensionellt (3D) och kan sedan rekonstrueras till 3D bilder. Med MR-teknik kan information även erhållas om vävnaders funktion, till exempel för kvantitativ blodflödesmätning.

Pulsåderbråck

Via stora kroppspulsådern (aorta) distribueras blodet från hjärtat till kroppens alla organ. Den delen av aorta som passerar genom buken kallas bukaorta. Väggen på bukaorta kan försvagas och kärlet kan utvidga sig i ett pulsåderbråck (aneurysm). Faktorer som ökar risken för bukaortaaneurysm är bland annat ålder, högt blodtryck och vissa ärftliga sjukdomar som försämrar aortaväg-gens hållfasthet, men bakgrunden är i allmänhet kom-plex. Aneurysmets utvidgning fortskrider i allmänhet utan att patienten märker det och utgör en med tiden stor risk för patienten. Om aneurysmet brister avlider cirka 80% av patienterna av den resulterande inre blödningen. Bukaortaaneurysm utvecklas hos drygt 4% av män som är äldre än 65 år, och knappt hälften så många kvinnor i samma ålder. I yngre åldrar är sjuk-domen ovanlig. Även om befolkningens stigande ålder beaktas, sker en ökning av antalet bukaortaaneurysm. Hos de flesta patienter upptäcks bukaortaaneurysmet av en slump.

På 50-talet lärde man sig att operera aortaaneurysm. Den sjukligt utvidgande delen av aorta ersätts av ett konstgjort kärl (graft). Behandlingsresultaten är goda, men ingreppet är påfrestande för patienten med lång konvalescens som följd. Många äldre patienter är allt för svaga för att kunna opereras.

Endovaskulär behandling

I början av 90-talet började aortaaneurysm behandlas med endovaskulär teknik. I stället för att öppna buken och sy fast graftet, förs ett så kallat stent-graft in i aneurysmet via ett kärl i ljumsken. Inför en endovaskulär behandling måste aneurysmets utseende noggrant kartläggas för att rätt val av stent-graft skall kunna göras. Stent-graftet expanderas på plats i aneurysmet och pressas fast mot kärlväggens insida där kärlet ännu inte vidgat sig, det vill säga ovanför och nedanför aneurysmet. Ingreppet kan utföras i lokalbedövning och patienterna stiger upp påföljande dag. Intensivvård behövs sällan. I motsats till behandling av aortaaneurysm med öppen kirurgi, måste det inlagda stent-graftet följas under lång tid, sannolikt livslångt. Eftersom de flesta av dessa patienter är äldre och inte sällan även har andra sjukdomar, löper de en ökad risk för att utveckla njurpåverkan av de kontrastmedel som används vid CT och DSA. Med CT och DSA utsätts dessutom patienterna för strålning.

Syfte och resultat

Syftet med denna avhandling var att utvärdera MR med CE MRA som undersökningsmetod före och efter endovaskulär behandling av bukaortaaneurysm. I avhandlingen ingår fem delarbeten.

Delarbete I

Patienter, som behandlats för bukaortaaneurysm med den relativt nya tekniken endovaskulär inläggning av stent-graft behöver följas radiologiskt under många år. I detta delarbete visar vi att MR med CE MRA kan användas som uppföljningsmetod. Det är så vitt vi känner till det första publicerade arbete, som visar att MR med CE MRA kan göras på patienter med en MR-kompatibel stent-graft och att MR ger viktig information om behandlingsresultatet.

Delarbete II

Denna tekniska studie visar att MR-undersökning av en typ av bukaorta stent-graft (Vanguard) är säker utan ferromagnetisk påverkan och utan uppvärmning. Stent-graftet ger små metallartefakter, som dock inte stör bildanalysen. Dessutom kan kvantitativ blodflödesmätning utföras på patienter med bukaorta stent-graft.

Delarbete III

MR med CE MRA jämförs med CT och DSA för mätning av aorta och aneurysmet inför behandling med stent-graft. Studien visar att MR-måtten sannolikt är bättre för längdangivelse, men förbättrad MR teknik krävs för pålitliga diametermått.

Delarbete IV

Kostnaden för radiologisk uppföljning av patienter behandlade med bukaorta stent-graft analyseras. MR med CE MRA är mer kostnadseffektivt än CT med DSA, eller CT-angiografi, om man tar hänsyn till risk för njurpåverkan orsakad av det jodhaltiga kontrastmedel som används vid de sistnämnda undersökningarna.

Delarbete V

Resultaten av en längre tids (8–84 månader) uppföljning med MR med CE MRA av patienter behandlade med två olika typer av bukaorta stent-graft (Stentor och Vanguard) redovisas. Komplikationer och behov av ytterligare behandling visade sig vara vanliga. Studien visar att dessa patienter måste följas under lång tid, sannolikt livslångt, efter endovaskulär behandling.

Sammanfattning

Avhandlingen visar att MR med CE MRA kan vara den bästa uppföljningsmetoden för patienter med bukaortaaneurysm endovaskulärt behandlade med MR-kompatibla stent-grafter. MR med CE MRA bör vara uppföljningsmetoden för patienter med nedsatt njurfunktion.

Introduction

Abdominal aortic aneurysms

An aneurysm is defined as a focal dilatation of the aorta involving an increase in diameter of at least 50% as compared with the expected normal diameter (Johnston et al. 1991). Aneurysms are often multiple. Ninety-five percent of all abdominal aortic aneurysms (AAA) affect the infrarenal aorta.

The prevalence of AAA has increased significantly during the last three decades, and is age and sex-dependent (Bengtsson et al. 1992). In a retrospective necropsy study from the city of Malmö, AAA were found in 4,300/100,000 men and 2,100/100,000 women (Bengtsson et al. 1992). Rupture of an AAA is responsible for 1–2% of deaths in men aged more than 65 years in western countries (St Leger et al. 1996). In the study by Drott et al. the incidence of ruptured AAA in the city of Gothenburg increased from 4.1/100,000 during 1970–1979 to 6.9/100,000 during 1980–1988 (Drott et al. 1992). The mean incidence of ruptured AAA in a well-defined geographic area in Finland was 6.3/100,000 (Heikinnen et al. 2002). The overall mortality of AAA rupture is approximately 80% (Kantonen et al. 1999). The costs of emergency open surgery are significantly higher compared with elective repair of AAA. The mortality in elective repair is 5–10% (Jepson et al. 1997, Ascher et al. 1999).

The pathogenesis of AAA is complex. Abdominal aortic aneurysms have usually been characterized as atherosclerotic but it would be more accurate to describe most aneurysms as non-specific. Several factors seem to have an important role, hypertension, smoking, high blood cholesterol, genetic predisposition, acquired biochemical alterations in the structural matrix of the aortic wall, and hemodynamic mechanical factors (Ernst 1993). Marfan syndrome, a connective tissue disorder, predisposes for aneurysmal formation (Hollister et al. 1990). Mycotic aneurysms due to syphilis were common earlier. However, the introduction of modern antibiotics has markedly reduced the incidence of infectious aneurysms.

Repair of abdominal aortic aneurysms

Open surgical repair

Modern treatment of AAA began in 1951, when Dubost performed the first successful aortic resection of an aneurysm (Dubost et al. 1952). Indication for repair of AAA must be made on an individual basis. Recommendations for repair are all symptomatic or ruptured AAA, and for all asymptomatic aneurysms more than 5 cm in diameter (Ernst 1993, Watson et al. 1997).

The extensive abdominal incision, mobilisation of the intestine to gain access to the retroperitoneum, aortic clamping and declamping as well as intraoperative blood loss, contribute to the traumatic effects of open surgical repair (Chen et al. 1996). Open surgical repair is quite effective in the lower surgical risk population, with a morbidity and mortality rate ranging from 0–8% (Zarins and Harris 1997). However, in the population with high risk level, more than 90 years of age and severe cardiac, pulmonary and renal concomitant disease, the mortality and morbidity significantly increase, with a mortality rate ranging from 8 to 30% (Zarins and Harris 1997). The development of less invasive techniques to treat AAA derived from the necessity to reduce mortality and morbidity.

Endovascular repair

The introduction of the percutaneous technique for arterial catheter insertion by Seldinger in 1953 had the greatest impact on the future development of endovascular interventions (Seldinger 1953). In 1991 Parodi and Volodos independently reported the first endovascular repair of infrarenal AAA (Parodi et al. 1991, Volodos et al. 1991). Ten years and more than 10,000 endovascular repairs later, some vascular surgeons remain sceptical, while others have embraced everything endovascular (Chuter 2002).

Endovascular repair, as opposed to open repair, requires pre-procedural imaging with detailed anatomic information, particularly the relationship of the proximal aortic neck to the renal arteries. Successful endovascular repair of AAA is a multidisciplinary effort. The contribution of each discipline varies between centres but usually involves a surgical team for the performance of the cut-down and access of the femoral arteries, and an interventional radiology team for the introduction of the delivery system and stent-graft placement. High-quality fluoroscopic imaging during the procedure is most important. Currently, most procedures are performed with epidural anaesthesia and conscious sedation reducing the overall length of hospitalization (Uflacker and Robison 2001).

Long-term follow-up of endovascular repair, as opposed to open repair, is mandatory (Uflacker and

Robison 2001, Chuter 2002, Engellau et al. unpublished results 2002). The EUROSTAR (European collaborators on stent-graft techniques) registry is currently the most reliable source of information of endovascular repair of AAA since it contains data of several thousand patients.

In a cost study, the mean total hospital costs (including stent-graft costs) for endovascular AAA repair were higher than for open surgical repair ($ 20,716 vs $ 18,484). However, endovascular repair was associated with a decreased length of hospital stay and fewer intensive care unit admissions (Bosch et al. 2001). For endovascular repair there are additional costs of a long-time follow-up and possible endovascular reintervention and sometimes open surgical repair.

Stent-grafts

Long-term results of endovascular repair are scarce. The stent-grafts available are numerous, and new designs are marketed rapidly making accumulation of large patient series rare. The reporting of endovascular repair is thus hampered. In view of these difficulties it is important to present follow-up of stent-grafts, even if the results may well concern stent-grafts no longer in clinical use. General conclusions regarding endovascular repair of AAA need to be qualified by reference to a system which assess graft performance. Any such system must be a product of acquired experience, and follow-up of stent-grafts.

Conclusions regarding observed effects of certain stent-graft design features, some of which are common to several devices, can be drawn (Chuter 2002). For example, tapered, traceable delivery systems (≤ 20 French in diameter) rarely fail to traverse tortuous iliac arteries. Transmural barbs provide the most secure means of proximal attachment. Column strength is of little value. Proximal stent migration is becoming the primary late failure mode. Modular stent-grafts are more versatile than unibody stent-grafts. Fully-stented graft limbs are less prone to thrombosis than unstented graft limbs. Iliac implantation and low porosity are associated with lower rates of aneurysm dilatation in the absence of endoleak (endotension). Movement between the angle of the stent and overlying fabric will lead to graft erosion. Unpolished (black) nitinol is prone to fracture and a combination with a long trunk and short limb is more stable than a short trunk and long limb combination (Chuter 2002).

To improve the sealing of the stent-graft to the proximal aortic neck, new stent-graft designs have been developed that are anchored above the renal arteries with endograft fenestration to preserve renal and visceral vessel perfusion (Anderson et al. 2001). Another recent stent-graft design development is a branched stent-graft (Chuter unpublished results). A detailed presentation of the development of stent-grafts, and the currently available types is beyond the scope of this discussion. Comprehensive reviews of different stent-graft designs have been published elsewhere (May et al. 1997, Uflacker and Robison 2001, Chuter 2002).

MR compatibility of stent-grafts is listed at a website, http://www.mrisafety.com, which is continuously updated. Many nitinol stent-grafts have been tested and found safe for MR scanning.

Magnetic resonance imaging

In 1946, independently of each other, Block and Purcell described the theory/phenomenon of nuclear magnetic resonance (NMR) (Block et al. 1946, Purcell et al. 1946). Block and Purcell were awarded the Nobel Prize in physics in 1952 for their findings. The NMR imaging technique was first introduced by Damadian in 1971 (Damadian 1971) and Lauterbur in 1973 (Lauterbur 1973). With the introduction of NMR to the clinical environment, starting with brain (Holland et al. 1980) and abdominal (Hawkes et al. 1981, Smith 1981) imaging, the adjective nuclear was dropped and the technique was thereafter referred to as magnetic resonance imaging (MRI).

Basic principles

The MRI technique is based on the use of a strong magnetic field in combination with radio frequency (RF) signals. MRI is accomplished using an MR imager, which is a complicated system consisting of a magnet, additional magnetic gradient fields, a radio frequency emitter and receiver, and computer systems for control and image reconstruction.

Hydrogen nuclei (protons), exhibiting a property called spin, which are subject to an external magnetic field, become oriented parallel or anti-parallel to the magnetic field. Looking at the total spin population, there will be a few more spins which are aligned parallel to the magnetic field and this portion is often describe as the magnetisation vector. When an external radio frequency field is applied, the energy is absorbed by the nuclei which become excited to a higher energy state. The energy is subsequently reemitted and a signal can be picked-up by an antenna (coil). The intensity of emitted signal is dependent upon tissue or substance properties and the chosen imaging technique.

MRI requires spatial localization of the NMR-signal and this is accomplished through the use of additional magnetic gradient fields. Magnetic field gradients applied in three orthogonal directions is used to spatially code the signal and as a result, the signal behaviour can be observed in a small volume element

(voxels). The signal measured in MRI is weak and can only be observed because of the very large number of proton spins in our body. Therefore, one major concern in imaging is to obtain adequate signal-to-noise ratio (SNR) in the images. This can be accomplished in many ways, an increase in the main magnetic field strength, by averaging multiple measurements and through optimal choice of local coils (surface coil). MRI produces high-resolution, high-contrast two-dimensional image slices of arbitrary orientation, but can also be used as a volume imaging technique and three-dimensional volumes can be measured directly.

MRI provides excellent soft tissue contrast due to several different mechanisms, chemical, physical or physiological. Contrast is mainly determined by T1- and T2 - relaxation processes, but other parameters such as proton density, susceptibility effects, magnetization transfer, diffusion, perfusion and flow effects can also be relevant contrast-determining parameters. MRI is furthermore highly sensitive to motion and also capable of quantifying flow velocities and thus quantitating blood flow.

The T1- and T2-relaxation of a substance describes how the energy, which was emitted by the RF sender and used for exciting the spins is reemitted and both T1 and T2 is characteristic to the specific substance and also depends upon the field strength of the main magnetic field. An image can be e.g. T1-weighted or T2-weighted, which means that the T1- or T2-effects will be the dominant factor for image contrast. The desired contrast is achieved by appropriate image parameters settings for the pulse sequences used. T1-relaxation time, or longitudinal relaxation time, is the time constant which describes how the longitudinal magnetization vector is recovered after that it was affected by an excitation RF pulse in an MR experiment. T2 relaxation time, or transverse relaxation time, is the time constant with which signal is decaying in an MR experiment.

Regarding the imaging technique especially two parameters are important, the repetition time (TR) and the echo time (TE). The repetition time of a MR sequence, is the time over which a basic pulse sequence is repeated to acquire all the necessary data. The echo time (TE), is the time at which signal echoes are obtained relative to the initial excitation pulse. T1-weighted images are obtained by setting TE << T2 and TR << T1 for most tissues. T2-weighted images are obtained by setting TE >> T2 and TR >> T1 for most tissues (Schulthess and Smith1998).

k-space

The k-space is the time domain where the MR signal is represented, through a Fourier transform of the time domain data, a standard two-dimensional (2D) and three-dimensional (3D) image is obtained. Each point in the time domain data or k-space carries information needed for reconstruction of the whole MR image. Different parts of the k-space contribute to varying degrees to the spatial resolution and the contrast in the reconstructed MR image. The centre of the k-space is most important for image contrast. The periphery of the k-space contains information about image resolution. Each line in k-space corresponds to one detected signal (or echo) and the time between detection of two signals is often equal to the repetition time. The order in which data for different lines are collected can be varied. The concept of k-space, and where in the k-space the image contrast is encoded, is important for the synchronisation of the contrast agent injection and the MR angiography (MRA) scan.

Magnetic resonance angiography

The three main magnetic resonance angiography (MRA) techniques are:
1. Time of flight (TOF) MRA
2. Phase contrast (PC) MRA
3. Contrast enhanced (CE) MRA

All angiographic techniques enhance vascular MR signal. TOF MRA uses inflow effects where unsaturated moving spins enter the slice and give rise to a high signal. PC MRA relies on pixel-wise identification of the signal phase which is proportional to the flow. CE MRA makes use of a rapid bolus infusion of contrast agent, which results in T1 shortening and strong enhancement of vascular structures. Relative advantages are summarised in Table 1.

Contrast enhanced MRA

With the introduction of gradient echo (GRE) pulse sequences in the second half of the 1980s, shorter MR acquisition times were permitted. In 1993, Prince described intravenously (i.v.) contrast enhanced (CE) MRA of the aorta (Prince 1993). The ability to cover large field-of-views (FOV) within a single breath-hold made CE MRA particularly well suited for abdominal imaging, where respiratory motion had previously been a major source of artefacts (Prince 1995 Radiology).

Basic principles

Three-dimensional CE MRA is a versatile technique that combines speed, superb contrast and is easy to use. A fast 3D spoiled GRE sequence with minimum repetition time (TR) and echo time (TE), and flip angles (FA) ranging from 25° to 50°, is used to achieve heavy T1-weighting and minimum flow-related artefacts. The choice of FA is a compromise between T1-weighting (T1-weighting increases with larger FA) and SNR. To

Table 1. MR angiography (MRA)

	TOF-MRA	PC-MRA	CE-MRA
Effect	Inflow of magnetic spins	Phase shifts of spins	Contrast agent related T1-shortening
Acquisition	2D or 3D	2D or 3D	2D or 3D
Pulse sequence	Spoiled GRE, EPI possible	Flow sensitive GRE, EPI possible	Spoiled GRE, EPI possible
Imaging time	> 60 s (without EPI)	> 200 s (without EPI)	10–30 s
Flow artefacts	Yes	Yes	Few
Flow information	Qualitative	Quantitative	Minimal
Respiration artefacts	Yes	Yes	Minimal
Contrast agent	No	No	Yes

maintain SNR, a small FA is necessary when a short TR is used. With a 3D acquisition the SNR is higher, since the signal from each volume element is integrated over the whole scan period (acquisition time), as opposed to 2D imaging, where the signal acquisition is slice selective. A 3D acquisition permits higher spatial resolution with isotropic, or near isotropic voxels, whereas the resolution in the slice selection direction in 2D imaging is limited. Flow-related artefacts are minimal in CE MRA. Saturation effects are negligible, since vessel signal mainly is attributed to a reduction of blood T1, rather than to an inflow effect. In addition, signal loss due to phase dispersion in areas of turbulent flow is minimal in CE MRA.

Vascular enhancement is achieved by a gadolinium based contrast agent (0.05 to 0.3 mmol/kg), injected i.v. as a bolus at rates ranging from 0.5 to 4 ml/s, preferably with an automatic injector. The first pass of the contrast bolus provides a brief temporal window of high intravascular concentration, which in turn generates high signal intensity by means of T1 shortening of blood. Timing of the injected contrast agent with the MR scan is crucial. The best images are obtained when acquisition of the central portion of k space coincides with the maximum concentration of contrast agent in the vessel of interest. There should also be a good match between the duration of the contrast bolus and the length of the 3D sequence. Rapid variation in the vascular concentration of contrast agent during acquisition of the central portion of the k space can generate significant artefacts (Glockner 2001).

Contrast agents

Two different types of contrast agents are used in CE MRA, extra cellular and intravascular, depending on their type of distribution after i.v. injection. Both the extra cellular and intravascular contrast agents affect T1 and T2 relaxation rates.

Extra cellular contrast agents include the most commonly used contrast agents in MRI, the gadolinium-based contrast agents, which show rapid leakage to the interstitial space and are therefore preferentially used as first-pass agents in CE MRA.

Intravascular contrast agents, or blood pool agents, are confined to the intravascular space due to their size. The intravascular contrast agent exhibit delayed clearance from the blood vessels, with T1/2 in plasma in the range of hours, which allows prolonged scan times. A disadvantage of intravascular contrast agents is the coexistent signal in the veins that may obscure the arteries. The intravascular contrast agents have not yet been approved for clinical use.

Timing strategies

A variety of image acquisition and injection strategies have been described to maximize vascular contrast.

The simplest method with regard to bolus timing is the "best guess" method, in which a standard travel time from peripheral veins to central arteries is assumed, and the 3D sequence is timed so that the central portion of the k space is acquired at the presumed peak vascular contrast concentration (Prince 1998). However, the range of travel time is broad and depends on age, hydration state and cardiovascular status.

In the test bolus technique, in which 1–2 ml of contrast agent is injected, along with saline solution for flushing, and the vessel of interest is scanned approximately once per second. The travel time can be directly observed and then used to calculate the correct scan delay (Prince et al. 1995 Radiology, Prince et al. 1997). This method always yields MRA with excellent contrast. Disadvantages of the test bolus technique include residual contrast agent in the renal collecting systems from the test bolus, which can obscure visualization of branch vessels of the renal arteries during CE MRA, as well as the additional time required for the test bolus sequence.

Recent developments are fluoroscopic triggering and automated triggering, in which the vessel of interest is continuously scanned until the contrast bolus is directly observed or the signal intensity reaches a specific level, at which the 3D sequence is begun (Foo et al. 1997, Wilman et al. 1997). Centric phase encoding is used in conjunction with these techniques, so that central k space is acquired at the beginning of the scan when vascular contrast is maximal.

Aims

The overall aim of the study was to evaluate MRI with CE MRA as imaging method before and after endovascular repair of AAA.

The specific aims were:

- To assess the value of MRI with CE MRA as follow-up method of endovascularly repaired AAA (Paper I).

- To evaluate MR safety, ferromagnetism and heating, of a nitinol-supported stent-graft exposed to a 1.5 T MR system. To evaluate image artefacts from a nitinol-supported stent-graft in MRI with CE MRA and CT. To evaluate an extended MR protocol including velocity mapping (Paper II).

- To compare measurements for stent-graft planning for endovascular repair of AAA. Measurements obtained with MRI with CE MRA were compared with measurements obtained with DSA and CT. In addition, to compare MRA measurements obtained with the post processing techniques MIP and VRT (Paper III).

- To compare costs of follow-up methods in patients with endovascularly repaired AAA. Comparisons were made between MRI with CE MRA and the follow-up methods used in EUROSTAR, CT with DSA or CTA. The cost analysis included a risk analysis of contrast media induced nephropathy (Paper IV).

- To present mid-term results of endovascular repair of AAA with the Stentor and Vanguard stent-grafts assessed with MRI with CE MRA (Paper V).

Material and Methods

Patients

Between January 1995 and August 1998, 26 consecutive patients (17 men, 3 women; mean age 69 years, range 52–80 years) with infrarenal AAA were enrolled in this prospective study (Papers I–V). The patients were identified by CT and DSA as potentially suitable for endovascular repair and had been referred by vascular surgeons, Department of Surgery, Lund University Hospital. Two patients were converted to open repair in connection with the stent-graft implantation. One patient was only followed for one month and then died of malignant melanoma. These three patients were therefore excluded from the follow-up studies (Papers IV and V). The patients were included in Papers I–V according to Figure 1.

In Paper I, 15 consecutive patients with endovascularly repaired AAA (15 men; mean age 68 years, range 53–81 years) were included in a follow-up study.

In Paper II, metal artefacts from a nitinol-supported stent-graft were assessed in ten patients (8 men, 2 women; mean age 69 years, range 58–77 years). Inclusion criteria for the selected patients were, the bifurcated Vanguard,

CE MRA with a 512 matrix, MRI with CE MRA and CT examinations performed within a period of six months to avoid the possibility of increased graft angulation that could potentially increase the artefact size.

MR velocity mappings were performed before, and at one and six months after endovascular repair in 14 consecutive patients. Nine patients (8 men, 1 woman; mean age 70 years, range 58–77 years) had evaluable MR velocity mappings both before and after endovascular repair and were included for evaluation.

In Paper III, 20 consecutive patients (17 men, 3 women; mean age 69 years, range 52–77 years), identified by CT and DSA as potentially suitable for endovascular repair, were included in a measurement comparison study.

In Paper IV, 23 consecutive patients with endovascularly repaired AAA (20 men, 3 women; mean age 68 years, range 53–81 years) were used as an indicator of contrast media induced nephropathy in a cost analysis of follow-up methods.

In Paper V, 23 consecutive patients with endovascularly repaired AAA (20 men, 3 women; mean age 68 years, range 53–81 years) were included in a mid-term follow-up study.
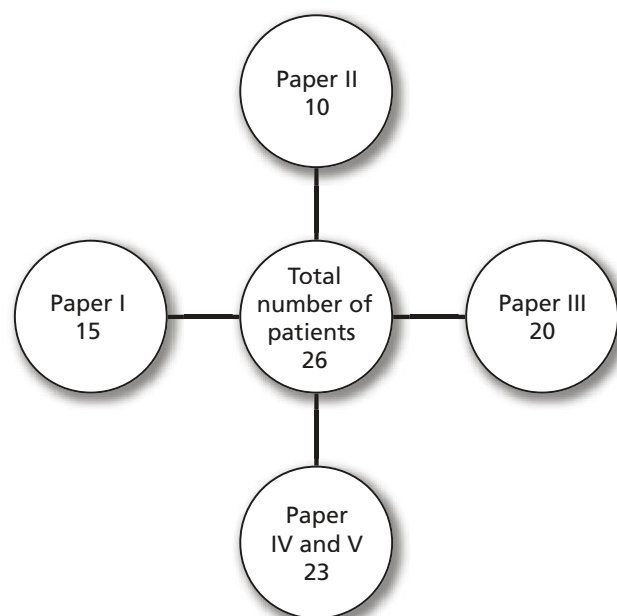
Ethics

The Ethics Committee at the Medical Faculty, Lund University, approved the studies. Informed consent was obtained from each patient.

Stent-grafts

A nitinol (nickel-titanium alloy, 55% nickel and 45% titanium), polyester covered, supported, self-expandable stent-graft (Mialhe Stentor™, MinTec, Bahamas) was used in 13 patients, in one a straight and in 12 a bifurcated stent-graft. A second generation (Vanguard™, Boston Scientific, Oakland, N.J., USA) stent-graft (Figure 2) was used in 11 patients, in one a straight and in 10 a bifurcated stent-graft. Vanguard was derived from the Stentor system with technologic improvements to the polyester, the nitinol frame, the attachment of the components and the introducer sheath (Becquemin et al. 1999). Neither of these stent-grafts is on the market due to disconnection of modular stent-graft components, suture and fabric tears and niti-

Figure 1. Number of patients in Papers I–V.
Paper I: Patient No 1–15.
Paper II: Patient No 14–26 (No 16, 22 and 23 were excluded).
Paper III: Patient No 7–26.
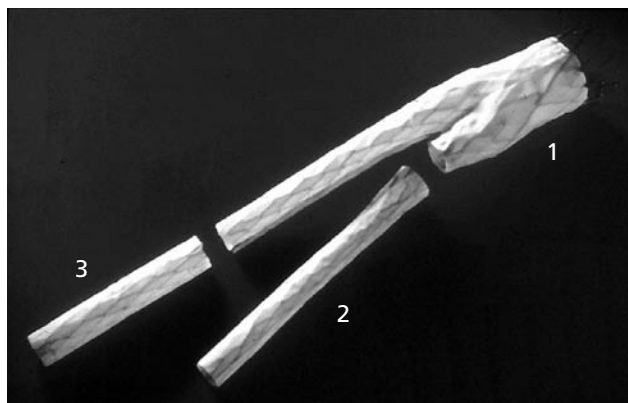Paper IV and V: Patient No 1–26 (No 13, 16 and 23 were excluded).

Figure 2. The bifurcated Vanguard stent-graft consists of two main components, the aortic component with a limb (1) and second limb (2). Limb extensions (3) can be added.

nol frame fracturing (Krajcer et al. 2001, Uflacker and Robison 2001, Chuter 2002).

In Paper I, the Stentor was used in 13 patients (one straight and 12 bifurcated). In two patients a bifurcated Vanguard was used.

In Paper II, MRI safety was evaluated at 1.5 T in a bifurcated, polyester covered nitinol-supported stent-graft with platinum markers (Vanguard). Imaging arte-facts were assessed on MRI with CE MRA and spiral CT in vivo as well as ex vivo. The Vanguard was selected because it was routinely used at our centre for endovas-cular repair of AAA.

In Paper V, the Stentor was used in 12 patients (one straight and 11 bifurcated) and the Vanguard was used in 11 patients (one straight and 10 bifurcated).

MR studies

A 1.5 T Siemens Magnetom Vision System (Siemens, Erlangen, Germany) with a maximum gradient strength of 25 mT/m and a minimum gradient rise time of 600µs was used. A total of 136 MR examinations (MRI with CE MRA) were performed (20 MRI with CE MRA were performed before endovascular repair). The first 115 examinations of the aorta were obtained using a body coil and thereafter a circular polarized body array coil (21 examinations) was used. The lumbar spine was examined in a spine array coil (first 62 examinations), in a body coil (following 53 examinations) and thereafter in a circular polarized body array coil (21 examina-tions). All coils were provided by the manufacturer. The MR sequences used are shown in Table 2. The present MR protocol is shown in Table 3. For the CE MRA the gadolinium-based contrast agent gadopentate diglu-mine (Magnevist®, Schering AG, Berlin, Germany) or gadodiamide (Omniscan®, Amersham Health, Oslo, Norway), both with a concentration of 0.5 mmol/ml was used. Information about the examination and breath-hold training was performed by a radiologist.

A 3D image volume extending from the origin of the superior mesenteric artery to the proximal femoral arteries was obtained before and after contrast injec-tion. A single arterial phase CE MRA was performed. A total of 40 ml gadopentate diglumine or gadodiamide was injected intravenously (i.v.) with an injection rate of 2 ml/s. During the first part of the study (90 examinations) hand injection was performed and later

Table 2. MR protocols

No of MR sequence exam.		TR (ms)	TE (ms)	Slice thickness (mm)	Matrix	FOV (mm)	Scan time (min:s)
136	T1 tse sag (ETL=3) Lumbar spine	600	12	4	300x512	300	3:03
39	T2 tse sag (ETL=15) Lumbar spine	4000	12	9	300x512	300	2:44
136	T1 se tra Abdomen and pelvis	580–680	14	10	148x256	350	5:03–5:46
39	T1 se tra + Gd Abdomen and pelvis	580–680	14	10	148x256	350	5:03–5:46
136	T2 tse tra (ETL=11–15) Abdomen and pelvis	3800–4205	99–120	10	176–180x256	350	3:26–5:07
39	3D MRA cor (3D FLASH) + Gd Aorta and iliac arteries	21	6	3D volume 70 Partition thickness 2.5	256x256–512	400	2:33
80	3D MRA tra (3D FLASH) + Gd Iliac arteries	21	6	3D volume 140 Partition thickness 5	256x256	350	2:33
97	3D MRA cor breath-hold (3D FLASH) ± Gd Aorta and iliac arteries	4–5	1.6–2	3D volume max 108 Partition thickness max 3.38	94–200x256–512	360–500	0:17–0:35

Table 3. Present MR protocol

MR sequence	TR (ms)	TE (ms)	Slice thickness (mm)	Matrix	FOV (mm)	Scan time (min:s)
T1 tse sag (ETL=3) Lumbar spine	600	12	4	300x512	300	3:03
T1 se tra Abdomen and pelvis	680	14	10	148x256	350	5:03
T2 tse tra (ETL=11) Abdomen and pelvis	4205	120	10	180x256	350	3:26
3D MRA cor breath-hold (3D FLASH) ± Gd Aorta and iliac arteries	4	1.6	3D volume 108 Partition thickness 3.38 Interpolated to 1.7	200x256	360	0:23

automatic injection by a power injector (46 examinations) was used. When hand injection was performed, it was used both for the test bolus (breath-hold MRA) and for the MRA examination, followed by a saline flush. The automatic injector was used both for the test bolus and for the MRA examination, followed by a saline flush. For the breath-hold MRA sequence the scan delay (from start of injection to scan start) [Scan delay = contrast travel time] had been determined by a test bolus sequence (T1 turbo FLASH, TR/TE 5.8/2.4 ms, FA 10° and 1 frame/s for 30 s). The image plane for the bolus test was a transverse plane of the abdominal aorta at the level of the mid body of the aortic stent-graft component (Figure 2). The test bolus volume was 2 ml. After subtraction the CE MRA dataset was reconstructed as maximum intensity projections (MIP) in coronal and sagittal projections (15 % increments) and multiplanar reconstruction (MPR) 5 mm slices in the transverse plane (Papers I–V).

CT studies

Spiral CT was performed on a Toshiba Xpress/SX, Japan. A total of 62 CT examinations were obtained (26 before endovascular repair, three were performed at other centres).

Images were obtained from just above the origin of the celiac artery and covering the iliac bifurcations, 1-second rotations were executed with a table speed of 5 mm/s. Collimation was 5 mm (pitch = 1), 90 ml Iohexol (Omnipaque® 300 mg I/ml, Amersham, Oslo, Norway) was given i.v. at a rate of 1.5–2.0 ml/s with a power injector. The scan delay was 60 seconds. The scans were reconstructed as single 7–10mm thick slices with an interval of 5–15 mm. Only transverse images were used for evaluation (Papers I–IV).

Angiography studies

X-ray angiography, performed as digital subtraction angiography (DSA) was performed on a Polydiagnost A (Philips, CONN., USA) equipment. A total of 43 DSA examinations were performed (26 before endovascular repair, two were performed at other centres).

A femoral artery was catheterised using the Seldinger technique (Seldinger 1953). A 6 French introducer was inserted, through which a 5 French pigtail universal measuring catheter (Angiomed, Karsruhe, Germany) with six side holes was placed with its tip in the lower aorta.

Iohexol (Omnipaque® 300 mg I/ml, Amersham, Health, Oslo, Norway), 40 ml/series, was injected with a power injector at a rate of 20 ml/s. Posterior-anterior and lateral projections of the abdominal aorta and posterior-anterior projection of the iliac arteries were obtained. Unsubtracted and subtracted images were used for evaluation. For the examination the patient was hospitalized one day (Papers I, III and IV).

Statistical analysis

In Paper II, possible differences of the mean flow in the aorta and in the femoral arteries were assessed. Comparisons were based on non-parametric statistics (Altman 1991). Wilcoxon signed-rank test for comparisons between the patients and Mann-Whitney U test for comparisons between the patients and the volunteers were used.

In Paper III, comparisons between methods and comparisons between observers were performed. Clinically accepted variations of measurement were chosen by the interventional radiologist performing the endovascular repair. The agreement between the methods, MRA-MIP vs. DSA, MRA-MPR vs. CT and MR-T1 vs. CT and between MIP vs. VRT, were assessed by comparing paired measurements matched on patient and observer.

Similarly, the agreement between two observers, were assessed by comparing paired measurements matched on patient and method. The distributions of the measurements for the different methods and for the observers, and of the corresponding pair-wise differences, were not normally distributed. Method comparisons were therefore based on non-parametric statistics (Altman 1991). The location of the data was summarised by the median and the spread of the data was summarised by the range or by relevant percentiles. The percentage of clinically unaccepted variations of measurement for each variable was reported. Wilcoxon signed-rank test was used as a test of no systematic difference. Note, however, that a statistically significant systematic difference might be indicated even though the difference is small and not clinically significant (Altman 1991). A possible association of patients and observers regarding clinically unaccepted variations of measurement between the methods, MRA-MIP vs. DSA and between MIP vs. VRT, were examined. This was done by pair-wise comparison between the methods matched on patient and observer. The results were tested with the Chi-square test against the frequencies of clinically unaccepted variations of measurement if no association existed (null hypothesis). The statistical computations were carried out using SPSS for Windows (release 10.0.05, SPSS Inc., Chicago, USA) and StatXact 5 (Cytel Software Corp., Cambridge, MA, USA).

In Paper V, Wilcoxon signed-rank test was used to compare the maximum aneurysm diameters observed for each patient (Altman 1991). Since earlier studies have shown that the only significant variable related to aneurysm size change was endoleak (Malina et al. 1997, Matsumura et al. 1997) the patients were separated into two groups, one with endoleak and one without endoleak. In each group, the maximum aneurysm diameters observed at adjacent follow-up points were compared. Since multiple comparisons were performed, P-values were also adjusted according to the Bonferroni method (Altman 1991). The statistical computations were carried out using SPSS for Windows (release 10.0.05, SPSS Inc., Chicago, IL, USA).

P-values less than 0.05 were considered statistically significant (Papers II, III and V).

MRI with CE MRA as follow-up of endovascularly repaired AAA—Paper I

Between February 1995 and November 1996 follow-up (median follow-up; 8 months, range 1-12 months) of endovascularly repaired AAA was performed. MRI with CE MRA, CT and DSA were performed at one month after stent-graft implantation. MRI with CE MRA was performed at 6 and 12 months, but on these occasions CT and DSA were added only when unexpected findings on MRI with CE MRA were seen. A total of 30 MRI with CE MRA were performed. In addition, six MRI examinations (performed between February 1995 and May 1995 of the abdominal aorta or the lumbar spine) for evaluation of the intramural thrombus organization, periaortic inflammation and vertebral body infarction, were included.

MRI with CE MRA

The first 21 examinations were performed with a non breath-hold MRA sequence, which was repeated in the transverse plane covering the iliac and the proximal femoral arteries. The last nine examinations were performed with a breath-hold MRA sequence.

Image analysis

Image analysis was made on films.

Stent-graft leakage (endoleak) was evaluated on MRA MIP and MPR transverse images correlated with T1-weighted transverse MR images. Endoleak was defined as the presence of contrast agent inside the aneurysmal sac outside the stent-graft. It was seen as high signal intensity on CE MRA (Figure 3) without high signal intensity in the corresponding location on the T1-weighted images. Minor stent-graft leakage (type III bifurcation endoleak) was defined as high signal intensity on CE MRA seen in the aneurysmal sac around the stent-graft bifurcation. Endoleak was also evaluated on CT and DSA.

Stent-graft morphology (graft deformation) was measured as the angle between the stent-graft body and left graft limb on CE MRA MIP and DSA, both posterior-anterior projections.

Aneurysm neck diameters were measured on T1-weighted transverse MR images directly beneath the most inferior renal artery, at the proximal margin of the aneurysm and at the midpoint between the two. The renal arteries were identified on MRA MPR transverse images corresponding to the T1-weighted images. The aneurysm neck diameters were also measured on CT. The measurements were performed with a ruler on film along the left-right axis of the image.

Maximum outer aneurysm diameter was measured on T1-weighted transverse MR images and on CT. The measurements were performed with a ruler on film along the left-right axis of the image, and always measured at the widest portion of the aneurysm.

Intramural thrombus organization was evaluated on T1- and T2-weighted transverse MR images. Unorganized thrombus was defined as high signal intensity on T1- and T2-weighted images, partially organized thrombus as inhomogeneous signal intensity with
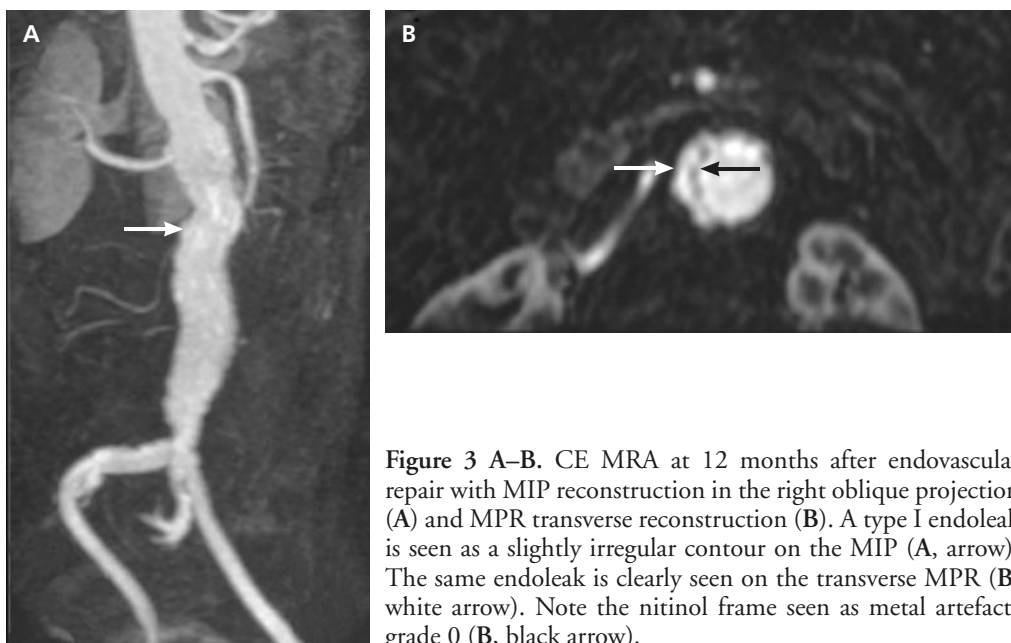
Figure 3 A–B. CE MRA at 12 months after endovascular repair with MIP reconstruction in the right oblique projection (**A**) and MPR transverse reconstruction (**B**). A type I endoleak is seen as a slightly irregular contour on the MIP (**A**, arrow). The same endoleak is clearly seen on the transverse MPR (**B**, white arrow). Note the nitinol frame seen as metal artefacts grade 0 (**B**, black arrow).

hyper-intense areas on T1- and T2-weighted images and organized thrombus as low signal intensity on T1- and T2-weighted images (Castrucci et al. 1995) (Figure 4 A–B).

Patency of lumbar arteries was seen as blood flow in the lumbar arteries evaluated on MRA MIP and MPR transverse images. Patency of lumbar arteries was also evaluated on CT and DSA.

Stent-graft blood flow was defined as signal intensity of the contrast agent in the stent-graft evaluated on MRA MIP and MPR transverse images. Stent-graft blood flow was also evaluated on CT and DSA.

Vertebral body infarction was evaluated on T1-weigthed sagittal MR images of the lumbar spine.

Periaortic inflammation was assessed on T1- and T2-weighted transverse MR images. Periaortic inflammation was also evaluated on CT.

MR safety and artefacts of a nitinol-supported stent-graft and MR velocity mapping—Paper II

Ferromagnetism, heating and artefacts were tested in a 1.5 T MR system ex vivo of a nitinol-supported stent-graft (Vanguard). Artefacts in vivo were assessed on MRI with CE MRA and on CT, performed between November 1996 and January 1999. Between May 1995 and December 1997, 47 MR velocity mappings were performed before, and at one and six months after endovascular repair. The accuracy of MR velocity mapping for our MR system was studied in six healthy volunteers (18 velocity mappings were performed between January 1996 and October 1996) (Amanuma et al. 1992). Comparisons of the flow measurements were made between the volunteers and the patients.

Assessment of ferromagnetism

Deflection force (translational movement) was measured using a previously described method (New et al. 1983). The stent-graft was suspended by a fine string, attached at the estimated centre of mass, to a specially constructed device (a plastic protractor mounted on a wooden stand) and placed at the portal of the magnet bore (Davis et al. 1981, New et al. 1983, Soulen et al. 1985, Teitelbaum et al. 1988, Schueler et al. 1999). The accuracy of this device is ± 0.5°. The portal of the MR system is the location of where the spatial gradient of the main magnetic field is at its highest level, and the deflection force is the strongest at this position (New et al. 1983, Soulen et al. 1985, Shellock and Crues 1988, Teitelbaum et al. 1988). The deflection force (F) is related to the deflection angle (θ) through the relation $F = m \cdot g \cdot \sin\theta / \cos\theta$, were m is the object mass and g is the gravitational constant. The deflection angle was measured two times.

The second evaluation of ferromagnetism involved a previously described technique (Shellock and Schatz 1991, Nogueira and Shellock 1994, Fagan et al. 1995, Shellock et al. 1995). The stent-graft was placed on a smooth film, with a millimetre scale beneath, on the MR table. The position of the stent-graft was noted and it was slowly introduced into the centre of the 1.5 T system. Close observations were made to determine any possible displacement of the stent-graft relative to the mm scale. The stent-graft was then turned in steps of 90° and the procedure was repeated three times (i.e. stent-graft positions 0°, 90°, 180° and 270°). The entire testing procedure was repeated three times.
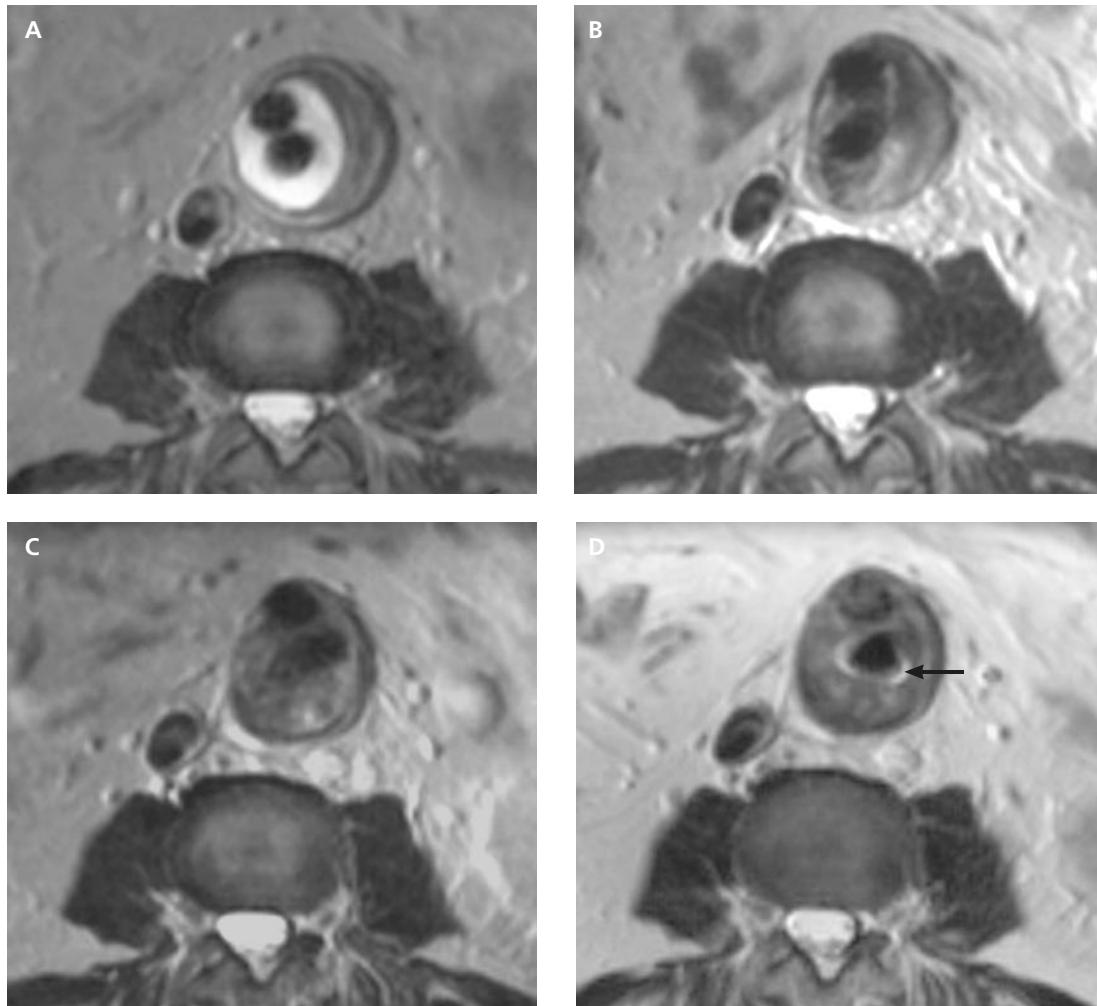
Figure 4 A–D. Aneurysm sac thrombus organization seen on MRI T1-weighted transverse images. Unorganized thrombus (1 month after endovascular repair) (**A**), partially organized thrombus (1 year) (**B**) and organized thrombus (3 years) (**C**). After reintervention with extension of the left graft limb due to stenosis (41 months after initial endovascular repair), the thrombus becomes partially organized (4 years) with high signal intensity around the graft limb (**D**, arrow).

Assessment of heating

The computed whole body specific absorbed ratio (SAR) value was determined based on the 1.5 T Siemens Magnetom Vision MR system. The SAR determinations were made with a phantom filled with water and a doping agent, and with an additional load inside the magnet. An assumed patient weight of 80 kg was used.

The stent-graft was placed in a phantom filled with saline solution at room temperature. Four single fluoroptic probes, Luxtron Model 3000 fluoroptic thermometry system (Luxtron, Santa Clara, CA, USA) were used. Three probes were attached directly to the covered stent-graft frame on the aortic component, at the mid body, limb and junction of the aortic component and second limb (Figure 2). One probe was placed in the surrounding saline solution to obtain a reference temperature. Sequences No 1–5 from our clinical follow-up protocol were tested (Table 4). The temperature was measured at 10–90 s intervals for a total imaging time of 18 minutes.

Excessive heat assessment was performed using the pulse sequence with the highest SAR value (sequence No 5). The stent-graft was placed in a phantom filled with saline solution and a doping agent at room temperature. For this phantom the computed whole body SAR value was 1.65 W/kg. The temperature was measured every minute for a total imaging time of 35 minutes. Three probes were attached directly to the stent-graft frame on the aortic component, at the proximal end, bifurcation and limb (Figure 2). One probe was placed in the surrounding saline solution 20 cm away from the stent-graft to obtain a reference temperature.

Assessment of artefacts

The presence and degree of stent-graft artefacts were assessed in vivo and ex vivo on MRI with CE MRA and CT by two independent observers. In case of differences joint reassessment was done. On MRI with CE MRA sequences No 2, 3, 5 and 6 were assessed (Table 4). On CT transverse 5 mm reconstructions were used.

Table 4. MRI with CE MRA sequences used in assessment of heating and artefacts

Sequence No	TR (ms)	TE (ms)	FA (°)	Slice thickness (mm)	FOV (mm)	Matrix	No of acquisitions	BW (Hz/pixel)	No of partitions	Scan time (min:s)	SAR (W/kg)
1. T1 tse sag (ETL=3)	600	12	120[a]	4	300	300x512	3	195		3:03	0.56
2. T2 tse tra (ETL=11)	3800	99	180[a]	10	350	176x256	5	130		5:07	1.05
3. T1 se tra	580	14		10	350	148x256	4	150		5:46	1.35
4. T1 turbo FLASH	3.3	1.4	15	10	300	128x128	1 (40[b])	488		0:40	0.23
5. MRA cor bh[c] 3D FLASH	5	2	50	3D volume 108 Partition thickness 3.0	500	192x512	1	488	36	0:35[d]	1.67
6. MRA cor bh[c] 3D turbo FLASH	4.6	1.8	30	3D volume 108 Partition thickness 3.38 Interpolated to 1.7	500	200x512	1	390	32	0:23[d]	1.16

[a] Flip angle refers to the refocusing pulse in the turbo spin echo sequence.
[b] Measurements for determination of circulation time.
[c] Breath-hold, [d] Breath-hold duration.

For the ex vivo assessments the stent-graft was placed in a phantom filled with saline solution and a doping agent. A metal artefact in a patient during MR imaging is typically seen as a local or regional distortion of the image, and/or as a signal void (Shellock 1998 Pocket guide, Hilfiker et al. 1999). We defined artefacts on MR imaging as a signal void with an extension beyond the size of the metal net in the stent-graft wall, or as a signal displacement. The beam hardening effects seen on CT were defined as artefacts (Figure 5). Artefacts were assessed at three levels of the stent-graft on the aortic component, at the proximal end, mid body and the junction of the aortic component and second limb (Figure 2). A modified, previously published method of grading was used both for MR imaging and for CT (Teitelbaum et al. 1988, Nogueira and Shellock 1994, Fagan et al. 1995, Shellock et al. 1995).

MR velocity mapping
Flow measurements by MR velocity mapping with velocity encoding (VENC) 150 cm/s and a TR/TE of 24/5 ms were performed in the patients and in the volunteers, in the abdominal aorta above the celiac trunk and in the femoral arteries at the level of the upper margin of the symphysis.

Flow analysis was performed on a workstation (Sun Microsystems, Mountain View, California, USA) with a specially designed evaluation program (RADGOP, Context Vision, Linköping, Sweden) with features for background phase correction, positioning of a ROI in either the conventional or the phase image, as well as repositioning/reshaping of the ROI in each image.

Two background ROIs were placed at equal distances from, and at opposite sites of, the vessel ROI to compensate for linear phase variations in the images. Flow was calculated by multiplying the average background-corrected velocity by the area of the ROI. Mean vessel flow was obtained by averaging flow values over a whole cardiac cycle. No correction for partial-volume effects was incorporated in the evaluation program.

Measurements for stent-graft planning before endovascular repair—Paper III

Between January 1995 and November 1998, patients with infrarenal AAA were enrolled in this study. The patients were identified as potentially suitable for endovascular repair by CT and DSA, the imaging methods used for stent-graft planning at our centre. For the study, MRI with CE MRA was also performed. Measurements for stent-graft planning were performed on MRI with CE MRA, DSA and CT. In addition, MRA measurement comparisons were made between the post processing techniques maximum intensity projections (MIP) and volume rendering technique (VRT).

Measurements
Measurements were performed on MRI with CE MRA, DSA and CT individually by three radiologists. Five measurement variables for stent-graft sizing were chosen by the radiologist performing the stent-graft repair (Figure 6). The measurements on MRI with CE MRA were made on a PACS workstation (Picture Archiving
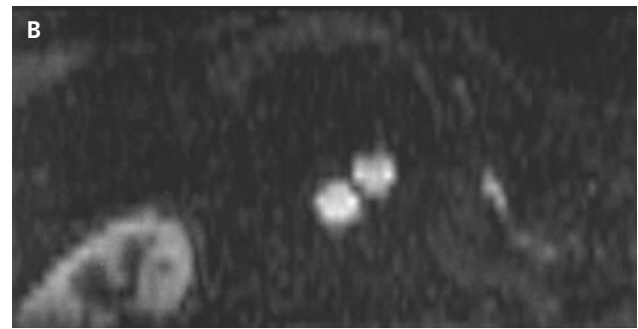
Figure 5 A–D. In vivo artefacts seen at the stent-graft limb junction; CE MRA MIP reconstruction in the posterior-anterior projection (artefact grade 0) with tapering of the stent-graft frame (arrow) (**A**), MPR transverse reconstruction (grade 0) (**B**), MRI T2-weighted transverse image (grade 1+) (**C**) and CE CT transverse image (grade 4+) (**D**). Artefact grade 0 = signal void corresponding to the thickness of the metal net of the stent-graft wall, grade 1+ = artefact smaller than the thickness of the metal net of the stent-graft wall, grade 4+ = severe beam hardening effects.
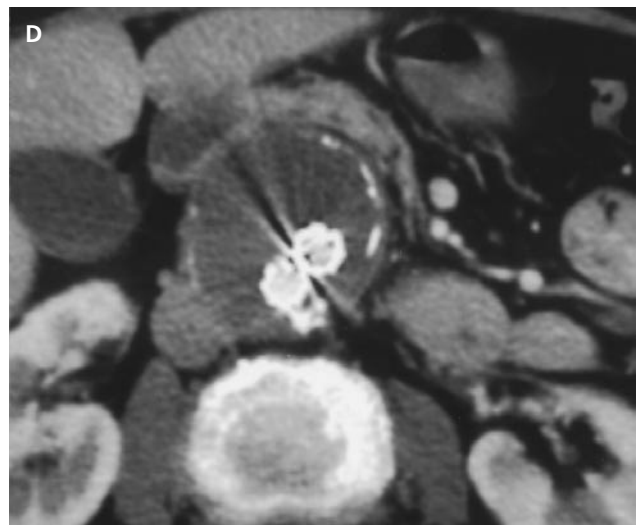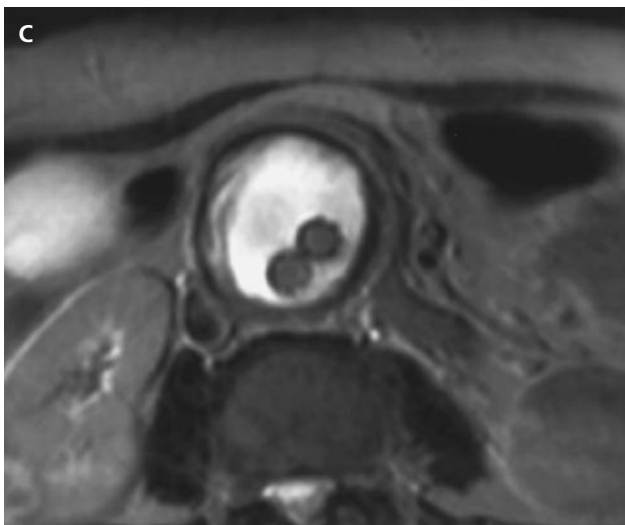
and Communication System) with the software system VRS Report (Cedara Software Corporation, Canada). The window settings were optimized by each observer. The measurements on DSA were made with a soft ruler on film. The measurements on CT were performed with a ruler on a film viewer with three-fold magnification.

The comparisons between the post processing techniques MIP and VRT using the same MRA data as above were performed at another centre with experience of VRT. Two radiologists measured the variables on MIP and VRT in consensus. The CE MRA datasets were loaded into a workstation (3D Virtuoso VA31, Siemens, Erlangen, Germany) equipped with VolumePro (Mitsubishi Precision Co, Ltd, Japan) accelerator graphics card for VRT and MIP post processing.

In VRT, a predefined preset ramp describing opacity, brightness and grey scale colours assigned to the voxel histogram for the volume rendering parameters was selected. For the MIP a simpler predefined preset, defining window level was used. A measuring tool that allows straight as well as curved measurements was used.

Costs in follow-up of endovascularly repaired AAA—Paper IV

Patients in a follow-up study (between February 1995 and May 2002, median follow-up; 36 months, range 8–84 months) of endovascularly repaired AAA, were used to assess the prevalence of pre-existing renal insuf-
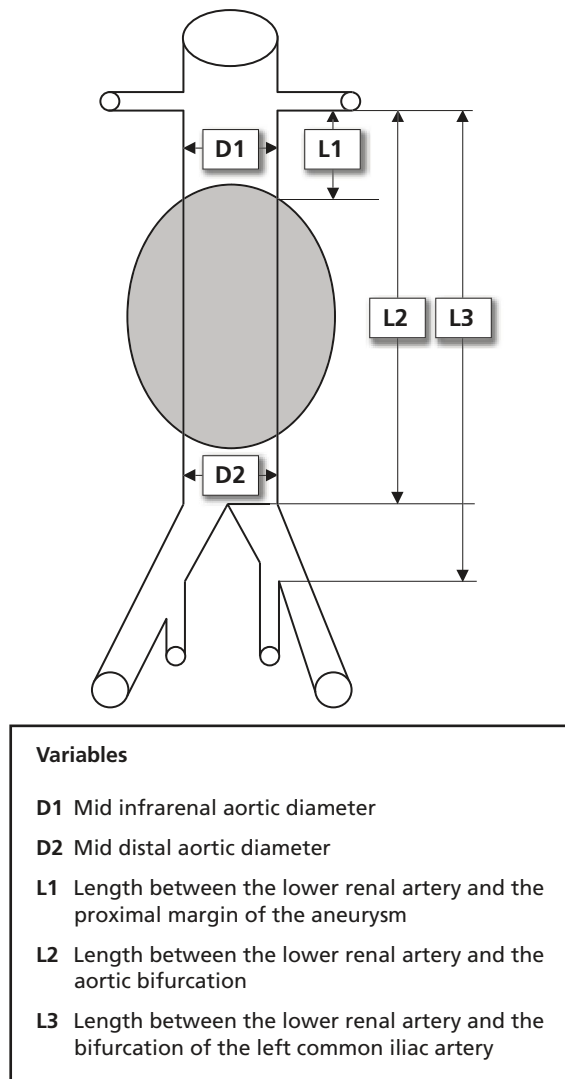
Variables

D1 Mid infrarenal aortic diameter

D2 Mid distal aortic diameter

L1 Length between the lower renal artery and the proximal margin of the aneurysm

L2 Length between the lower renal artery and the aortic bifurcation

L3 Length between the lower renal artery and the bifurcation of the left common iliac artery

Figure 6. Measurement variables for stent-graft sizing.

ficiency. As the information obtained with MRI with CE MRA is comparable to CT and DSA (Engellau et al. 1998) our follow-up protocol consisted of MRI with CE MRA after the first year and then annually. In addition, we performed a conventional radiograph of the abdomen in posterior-anterior and oblique projections to identify possible fracturing of the stent-graft frame.

Costs for MRI with CE MRA, CT and DSA were based on 2001 prices from the hospital accounting systems (prices in Swedish crowns were converted to Euro ( ), exchange rate 9.21). The costs for CTA were based on the price at a centre with great experience of CTA, where the prices were comparable to the prices at our centre. As a conventional radiograph of the abdomen was done in conjunction with both MRI with CE MRA and CT, the extra cost of the examination was equal and therefore not included. We compared costs of a five years follow-up protocol including MRI with CE MRA, with two alternatives of a EUROSTAR follow-

up protocol, one with CT with DSA and the other with CTA.

To determine the frequency of diagnostic DSA, i.e. the number of DSA examinations minus the number of interventions, performed in addition to CT during a five year follow-up in a EUROSTAR protocol we used the expression:

No of diagnostic DSA / No of CT x No of follow-up occasions
(574/6 580 x 9=0.8)

Hence on average one diagnostic DSA was performed in addition to the CT examinations.

To address differences in costs due side effects, we concentrated on the risk of contrast media induced nephropathy (CMIN) under CT with DSA, and CTA. Based on the experience that CMIN may be associated with an average increase of four hospital days and may precipitate the need for renal dialysis (Oliveira 1999) (three to seven temporary renal dialyses with hospital stay are average in case of CMIN at our centre) we assumed that, five renal dialyses with five days hospital stay were required for patients with CMIN (4,515).

To estimate how high the risk (r) of CMIN with CT with DSA, and CTA has to be in order to make the costs equal to those of MRI with CE MRA during five years follow-up we used the expression:

$$\sum_{i=1}^{5}\left(MRI/MRA \times Z_i\right) = \sum_{i=1}^{5}\left(CT/DSA \text{ or } CTA \times Z_i\right) + \sum_{i=1}^{5} r\left(Y \times Z_i\right) \quad (1)$$

MRI/CE MRA = cost per MRI with CE MRA
CT/DSA or CTA = cost per CT with DSA, or CTA
Y = costs of five renal dialyses and five hospital days
r = risk of CMIN with CT with DSA, or CTA
Z_i = number of MRI with CE MRA, or CT with DSA, or CTA during year i.

From this we calculated r:

$$r = \frac{\sum_{i=1}^{5}\left(MRI/MRA \times Z_i\right) - \sum_{i=1}^{5}\left(CT/DSA \text{ or } CTA \times Z_i\right)}{\sum_{i=1}^{5}\left(Y \times Z_i\right)} \quad (2)$$

The expression assumed that the risk of CMIN is equal for every examination with CT with DSA, or CTA during the five years follow-up. It is also assumed that the risk of CMIN with MRI with CE MRA is zero (Schumann-Giamperi et al. 1990, Prince et al. 1996).

Mid-term results with the Stentor and Vanguard—Paper V

Between February 1995 and May 2002 follow-up with MRI with CE MRA (median follow-up; 36 months,

range 8-84 months) of endovascularly repaired AAA was performed. MRI with CE MRA was performed at 1, 6 and 12 months and thereafter annually after endovascular repair. A total of 116 MRI with CE MRA were performed. In addition, six MRI examinations (performed between February 1995 and May 1995 of the abdominal aorta or the lumbar spine) for evaluation of the intramural thrombus organization, periaortic inflammation and vertebral body infarction, were included. In addition, we performed a conventional radiograph of the abdomen in posterior-anterior and oblique projections to identify possible fracturing of the stent-graft frame.

MRI with CE MRA

During the first part of the study (70 examinations) hand injection was performed and later automatic injection by a power injector (46 examinations). The turbo-MRA sequence used in the last 57 examinations has a shorter acquisition time (17 s), which is achieved by shorter TR and partial k-space collection with zero filling. In addition, the image quality was improved by slice interpolation.

Image analysis

Image analyses were made on films between 1995 and 1999 and thereafter on a PACS workstation (Picture Archiving and Communication System) with the software system VRS Report (Cedara software Corporation, Canada).

The image analysis is described in Paper I. Additional analyses and definitions in Paper V are:

A previously described classification of Endoleak was used (White et al. 1998). Type I endoleak is due to inadequate or ineffective seal at the graft ends, type II is a retrograde flow from collateral branches, type III

arises from a defect in the graft fabric, inadequate seal, or disconnection of modular graft components and type IV is due to graft fabric porosity, often resulting in a generalized mild blush of contrast material within the aneurysmal sac. The previously described minor leakage in the thrombus around the stent-graft bifurcation corresponds to type III bifurcation endoleak in this follow-up material (Engellau et al. 1998).

Graft migration was evaluated as a change of the distance between the most inferior renal artery and the proximal nitinol frame seen as metal artefacts on T2-weighted transverse images. The renal arteries were identified on MRA MPR transverse images corresponding to the T2-weighted images.

Graft deformation is described in Paper I.

Graft limb stenosis was defined as decreased signal intensity in a graft limb evaluated on MRA MIP and MPR transverse images.

Aneurysm neck and maximum outer aneurysm diameters were remeasured on all follow-up examinations with a ruler on film along the left-right axis of the image.

The intramural thrombus organization is described in Paper I (Figure 4).

Miscellaneous: Patency of lumbar arteries was evaluated on MRA MPR transverse images. Thrombosis was defined as the absence of signal intensity of the contrast agent in the stent-graft evaluated on MRA MIP and MPR transverse images. Vertebral body infarction was seen as sharply defined serpentine borders with low signal intensity evaluated on T1-weigthed sagittal images of the lumbar spine. Periaortic inflammation was seen as high signal intensity on T2-weighted transverse images (Norgren et al. 1998). Graft frame fracture can be detected on conventional radiographs or DSA.

Results and Discussion

General considerations

MRI with CE MRA provides the relevant information needed for follow-up of endovascular repair of AAA (Engellau et al. 1998, Golzarian and Struyven 2001, Haulon et al. 2001) but larger studies may be required to affirm these results. In addition, MRI with CE MRA is non-invasive, uses a non-nephrotoxic paramagnetic contrast agent and does not expose the patient to ionizing radiation (Engellau et al. 1998). The recommendations of the European Union Medical Exposure Directive are to use a modality without ionizing radiation when it is possible to obtain the same diagnostic results (Beavers 2000).

MR safety and artefacts

MR procedures may be contraindicated for an endovascularly repaired patient primarily because of the risk associated with movement or dislodgement of a ferromagnetic stent-graft. Only stent-grafts that have been thoroughly tested and determined to be safe for patients should be accepted for MR scanning. Previous studies have shown that MR procedures may be performed safely if the metallic object exhibits none, or negligible ferromagnetism, in the sense that the metallic object is not affected by the static magnetic field (Nogueira and Shellock 1994, Shellock 1998 AJR, Shellock 1998 Pocket guide, Schueler et al. 1999). Most metallic objects tested for magnetic field attraction were assessed at 1.5 T. For MR systems with higher magnetic field strengths stricter safety recommendations may have to be considered (Shellock 1998 Pocket guide). The stent-graft typically becomes incorporated into the vessel wall primarily due to tissue in-growth approximately six weeks after stent-graft placement (Shellock 1998 Pocket guide).

Previous studies have shown that only minor temperature changes occur in association with a MR procedure involving metallic objects (Fagan et al. 1995, Shellock et al. 1995, Shellock 1998 AJR, Schueler et al. 1999). Therefore, heat generated during a MR procedure involving a patient with a metallic object does not appear to be a substantial hazard.

Metal artefacts may affect image quality and the interpretation of the diagnostic information (Laissy et al. 1995, Shellock 1998 Pocket guide, Hilfiker et al. 1999). The relative amount of image distortion and artefacts depends on, the magnets susceptibility, the quantity, shape, orientation and position of the metallic object in the body, as well as the imaging techniques used. A metal artefact in a patient during MR imaging is typically seen as a local or regional distortion of the image, and/or as a signal void (Shellock 1998 Pocket guide). In the study by Klemm et al., it was found that a parallel orientation of intravascular stents in the magnetic field leads to significantly smaller signal voids and can provide better visibility of the lumen (Klemm et al. 2000).

Contrast media induced nephropathy

Intravenous non-ionic monomeric iodinated contrast media show a 2–3 times higher incidence of total adverse events (i.e. general and renal) than i.v. gadolinium-based contrast agents (Niendorf et al. 1993). Gadolinium-based contrast agents are regarded as non-nephrotoxic in clinically recommended doses for MRI and CE MRA (Prince et al. 1996, Shellock and Kanal 1999). The total incidence of adverse events for gadolinium-based contrast agents appears to be less than 5%, and the incidence of any single adverse event is approximately 1% or less in all patients (Shellock and Kanal 1999).

Due to a required long-term follow-up and the fact that the endovascularly repaired AAA patients often are old with concomitant diseases, choosing a follow-up method with a low risk of complications is important. CMIN is defined by an increase in serum creatinine concentration by more than 25% or 44 µmol/L occurring within three days following intravascular administration of the contrast media and in the absence of an alternative aetiology (Morcos and Thomsen 2001). The incidence of CMIN is low in people with normal renal function and without any significant risk factors, varying between 0 and 10% (Krause 1998), with an average incidence of 3% in the largest studies (Rudnick et al. 1994). Pre-existing renal insufficiency increases the risk of CMIN, and an incidence of 12–27% has been reported in prospective controlled studies (Morcos and Thomsen 2001). Known risk factors are age over 70 years, myeloma, diabetic nephropathy, congestive heart failure, dehydration and concurrent use of nephrotoxic drugs (Morcos and Thomsen 2001).

MRI with CE MRA as follow-up of endovascularly repaired AAA—Paper I

In this study, we found that MRI with CE MRA pro-

Table 5. Outcomes for 15 patients endovascularly repaired for AAA (Paper I)

Outcome	n	(%)
Major endoleak	4	(27)
Minor endoleak	10	(67)
Graft deformation	8	(73)
Patency of lumbar arteries	15	(100)
Stent-graft blood flow	15	(100)
Vertebral body infarction	2	(13)
Periaortic inflammation	2	(13)
Secondary endovascular repair	2	(13)
Conversion to open repair	2	(13)

vided the relevant information needed for follow-up of endovascularly repaired AAA. MRI was the sole method demonstrating intramural thrombus organization and vertebral body infarction.

A summary of the outcomes for the patients is shown in Table 5.

Stent-graft leakage (endoleak) was seen as a hyper intense region within the otherwise hypo intense aneurysm sac on CE MRA. The CE MRA images must be correlated with the T1-weighted MR images, where no hyper intensity was found, since methaemoglobin formation in the aneurysm sac may also be hyper intense on CE MRA. Major stent-graft leakage (endoleak) was found in four (27%) of the patients and was equally well demonstrated by MRI with CE MRA, CT and DSA. In the EUROSTAR registry the incidence of endoleak varies from 10–44% (Cuypers et al. 1999). Two patients were endovascularly repaired, one patient treated with emergency open surgery and in one patient the endoleak ceased spontaneously. The patients with major endoleak had no increase of the maximum outer aneurysm diameter. This was not in agreement with previously published work where the aneurysm diameter increased in case of endoleak (May et al. 1995, Blum et al. 1997, Broeders et al. 1997, Malina et al. 1997, Matsumura et al. 1997). Explanations for these differences may be that the measurements in our study were crude made with a ruler on films always along the left-right axis to the vessel. Minor stent-graft leakage (type III bifurcation endoleak) was seen in all but one patient with the bifurcated Stentor, with a seam at the bifurcation responsible for the endoleak. Minor endoleak was not seen in the two patients with the bifurcated Vanguard, with no seam at the bifurcation. Minor endoleak was only seen on CE MRA, which has a high sensitivity to detect endoleak (Golzarian and Struyven 2001, Haulon et al. 2001). The beam hardening artefacts on CT concealed the type III bifurcation endoleak (Figure 5D).

Stent-graft morphology (graft deformation) with angulation (5–40%) was found in eight (73%) of the patients with bifurcated stent-grafts on CE MRA and DSA.

Change of aneurysm neck diameters was found in two patients, in one an increase by 3 mm and in one a decrease by 4 mm. However, these measurements were only performed on two follow-up occasions. When all aneurysm neck diameters were remeasured, no change was found (Paper V). Change of maximum outer diameters was found in nine patients, in two an increase by 4–9 mm and in seven a decrease by 2–22 mm. The diameter measurements were equally well performed on MRI and CT, but could not be measured on DSA.

The intramural thrombus organization could only be characterized on MRI. The complexity of the intramural thrombus organization over time is shown in Figure 7 (1 month to 1 year). The high signal intensity in the aneurysmal sac thrombus seen on T1- and T2-weighted transverse images in patients with unorganized or partially organized thrombus is consistent with hematoma (coagulated blood).

Patency of lumbar arteries was seen in all patients on CE MRA and DSA. Patency of lumbar arteries was generally not possible to see on CT.

Stent-graft blood flow was seen in all patients on CE MRA, CT and DSA. On CE MRA decreased signal intensity was seen at the limb junction in twelve patients. DSA showed a minor stenosis at the limb junction in three of these patients. On CT the limb junction could not be evaluated due to the beam hardening artefacts. The decreased signal intensity seen on CE MRA is due to the tapering of the stent-graft frame at the limb junction and possibly minor metal artefacts (Figure 5A).

Vertebral body infarction was seen in two patients (13%) at the one month follow-up which persisted at the 6 and 12 month follow-up respectively. MRI was the sole method demonstrating this. Both patients had clinical signs of microembolization to the spinal cord and/or lumbosacral plexus with partial paresis of one leg.

Periaortic inflammation was seen in two patients (13%) at 1 month follow-up with complete regression at 6 months follow-up. Periaortic inflammation was seen in both patients on MRI, but only in one patient on CT. This was in agreement with previous work suggesting MRI to be more sensitive in detecting inflammation (Tennant et al. 1993, Spartera et al. 1994).

This study had some limitations. Method comparisons were made between MRI with CE MRA, and CT and DSA, since CTA was not performed at our centre. However, there is no reason to believe that CTA would have yielded relevant abformation other than the combination of CT with DSA as a reference for comparison. MRI with CE MRA was only compared with both CT and DSA at one month follow-up. When we assessed
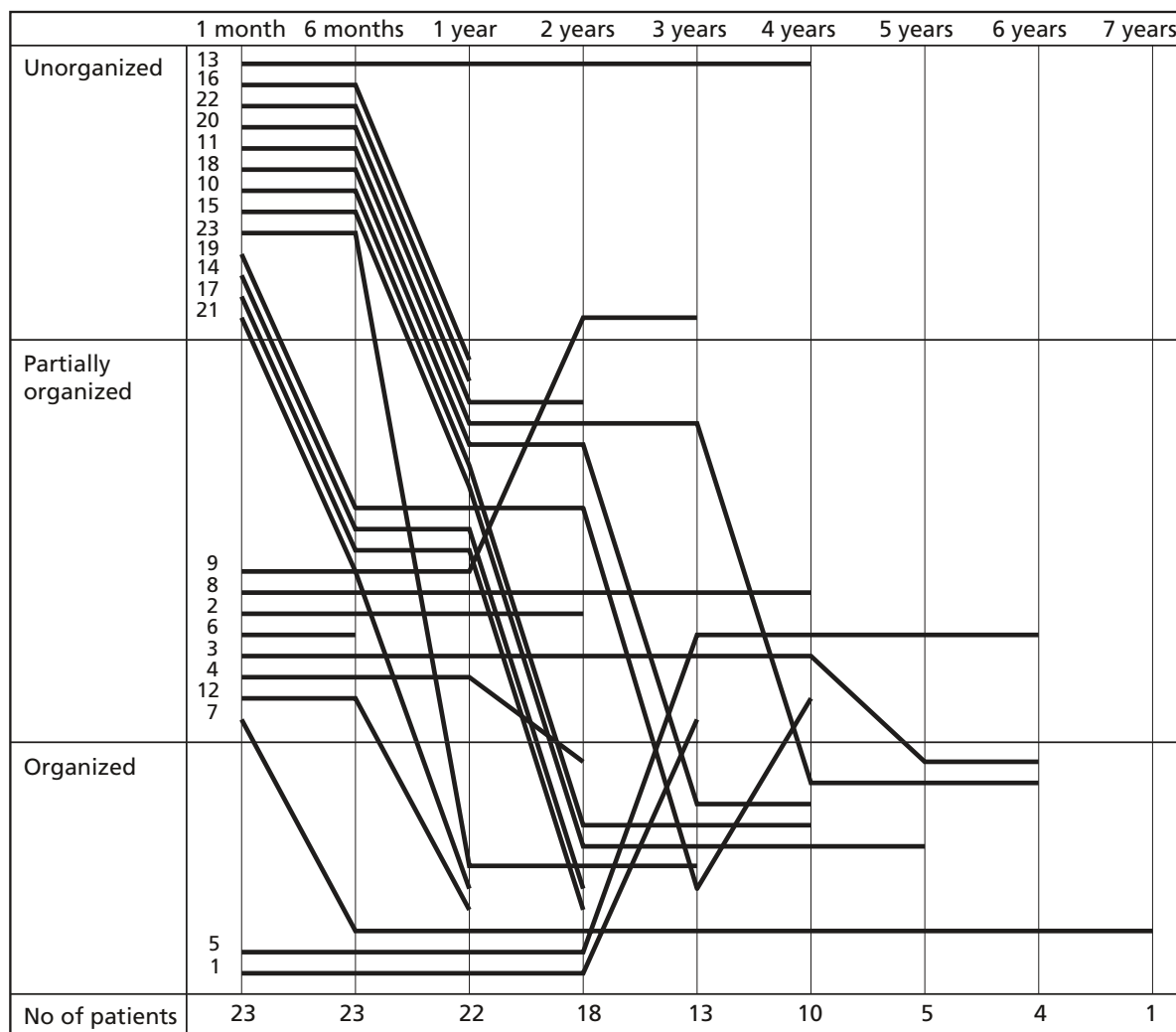
Figure 7. Complexity of the intramural thrombus organization over time after endovascular repair of AAA. Unorganized thrombus was defined as high signal intensity on T1- and T2-weighted MR images, partially organized thrombus as inhomogeneous signal intensity with hyper-intense areas on T1- and T2-weighted images and organized thrombus as low signal intensity on T1- and T2-weighted images. Disorganization of the thrombus correlates to endoleak and secondary intervention.

the methods of follow-up we found that MRI with CE MRA provided the relevant information. Since, MRI with CE MRA is non-invasive, uses a non-nephrotoxic paramagnetic contrast agent and does not expose the patient to ionizing radiation, we did not find it ethically justifiable to perform all three methods of follow-up. However, we did perform CT and DSA at 6 and 12 months follow-up to confirm unexpected findings on MRI with CE MRA.

MR safety and artefacts of a nitinol-supported stent-graft and MR velocity mapping—Paper II

In this study, we found that MRI in a 1.5 T system may be performed safely in patients endovascularly repaired with the nitinol-supported stent-graft (Vanguard). MRI with CE MRA provided diagnostic image information with only minor metal artefacts. Image evaluation on

CT can be disturbed at the graft bifurcation and limb junction by the beam hardening artefacts. MR velocity mapping was not included in our routine protocol.

Ferromagnetism: The deflection angle of the stent-graft was 0°, resulting in a zero deflection force. No displacement of the stent-graft was noted. Therefore it is unlikely that the Vanguard stent-graft would displace in vivo as a result of the static magnetic field of MR systems up to 1.5 T (Shellock et al. 1995, Shellock 1998 Pocket guide, Schueler et al. 1999). The non-ferromagnetic quality of nitinol has been reported in studies of other bioimplants constructed of similar materials (New et al. 1983, Shellock et al. 1995, Shellock 1996, Shellock 1998 Pocket guide).

Heating: The SAR values for sequences No 1–6 is presented in Table 4. In the first part of the phantom measurements, no temperature change was detected at the fluoroptic probes attached to the stent-graft or in the surrounding saline solution (i.e. the reference site).

Regarding the excessive heat assessment, an overall temperature raise of 0.9–1.1°C for the fluoroptic probes was measured during the entire imaging time. No temperature difference was noted between the probes attached to the stent-graft or in the surrounding saline solution. Within experimental error margins, no excessive heating of the nitinol stent-graft immersed in saline solution was observed ex vivo in this study. The in vivo situation may be even more favourable, since blood is flowing rapidly through the stent-graft providing heat regulation (Zhang et al. 1993). Previously published results of bioimplants tested for heating has shown that a temperature increase of less than 1.0°C is unlikely to be of any physiological consequence (Zhang et al. 1993, Fagan et al. 1995, Shellock et al. 1995, Shellock 1996).

Artefacts: MR artefacts associated with stent-grafts are related to the geometry and the metal composition of the stent-graft (Hilfiker et al. 1999, Klemm et al. 2000). Increasing stent-graft angulation could potentially increase the artefact size (Engellau et al. 1998). Thus we chose to relate the artefact size to the corresponding CT images instead of measurements of the stent lumen (Hilfiker et al. 1999). Sequences No 5 and 6 were evaluated as transverse MPR that made them comparable to the evaluation of sequences No 2 and 3 (transverse images) as well as to the transverse CT images. The artefacts produced by the nitinol stent-graft frame caused only minimal image distortion on MRI with CE MRA in vivo and ex vivo in this study. Locally on MRI in vivo, the artefacts were more pronounced in a few cases. This was due to the proximal row of barbs, double metal net at the junction, the platinum markers and overlapping metal net caused by stent-graft angulation (Engellau et al. 1998). The artefact extension into the stent-graft lumen was minimal and did not disturb the in vivo evaluation of the nitinol stent-graft. On CT the beam hardening effects at the graft limb junction, and hence also at the graft bifurcation due to the proximity, can disturb image evaluation.

Velocity mapping: The MR velocity mappings in the healthy volunteers were in agreement with previously published flow values (Amanuma et al. 1992). No significant differences in mean flow were found in the patients before and after endovascular repair. The mean flow in the aorta was significantly lower in the patients, both before and after endovascular repair, than in the healthy volunteers. However, no significant differences in mean flow in the femoral arteries were found between the patients both before and after endovascular repair, and the healthy volunteers. One explanation for this may be measurement uncertainties, especially in the smaller vessels, another may be the small number of patients and volunteers. MR velocity mappings were only evaluable in nine of the 14 patients, with velocity mappings made before and after endovascular repair. Reasons for unsuccessful or missing velocity mappings was, variations in heart rate during the examination, problems with the ECG-triggering and inability of the patients to cooperate for 20–30 additional minutes after the previous clinical MR protocol.

Measurements for stent-graft planning before endovascular repair—Paper III

In this study, we found that length measurements obtained with MRA-MIP were significantly shorter, but probably more correct, than those obtained with DSA. The diameter measurements obtained with MRI with CE MRA were more variable. Improvements of the CE MRA technique including VRT and a standardized determination of the vessel boundaries are needed for more reliable diameter measurements.

Endovascular stent-graft planning requires more accurate morphologic information and detailed measurements than open repair. The contour, length and diameter of the proximal aortic neck, the presence of thrombus, the angle between the proximal aortic neck and suprarenal aorta, the anticipated required length of the stent-graft, the quality and dimensions of the iliac arteries and the presence of any accessory renal arteries are relevant (Pattynama et al. 2001). MRI with CE MRA reveals complex, tortuous arterial anatomy, accurately delineates aneurysm size, including proximal and distal extent, mural thrombus, relationship to major vessels and number and location of renal arteries (Ecklund et al. 1994, Thurnher et al. 1997). MRI with CE MRA reveals iliac thrombus and aneurysms (Ecklund et al. 1994, Thurnher et al. 1997), but is less sensitive to the detection of calcification. The improvements of delivery systems have enabled the safe passage through tortuous and calcified iliac vessels, why the detection of calcification should be less important (Stanley et al. 2001). The 2D methods DSA and CT do not provide the required accuracy for sizing of stent-grafts as sole imaging methods (Beebe 1997, Broeders et al. 1997, Thurnher et al. 1997, Neschis et al. 2001). The 3D methods spiral CTA and MRI with CE MRA, provide more accurate information (Broeders et al. 1997, Thurnher et al. 1997, Armon et al. 1998) and CTA is the most widely used method for stent-graft planning.

The length measurements obtained with MRA-MIP were significantly shorter than those with DSA. Measurements may be overestimated on DSA by errors due to the imaging method as well as by the calibration method used. The length of the proximal aortic

neck (L1) is most crucial for secure anchoring of the stent-graft (Moritz et al. 1996, Thurnher et al. 1997). Our results showed a high percentage (77%) of pair-wise differences with clinically unacceptable variations of measurement for L1 (> ±2 mm) for MRA-MIP vs. DSA. One explanation for these differences could be the mural thrombus in the proximal portion of the aneurysm. DSA only delineates the vessel lumen and therefore tends to overestimate the length of the proximal aortic neck (L1) (Armon et al. 1998).Thus, the length measurements obtained by CE MRA are probably more correct due to the simultaneous access to transverse images showing the vessel lumen as well as the mural thrombus. Significant differences for L2 and L3 (Figure 6) were also found between MRA-MIP vs. DSA. The percentages of pair-wise differences with clinically unacceptable variations of measurements were smaller than for L1, which could be explained by the fact that we accepted larger variations for L2 and L3 than for L1. The lengths L2 and L3 could be interpreted as longer on DSA due to difficulties to determine the exact position of the bifurcations on a 2D method. The 3D method CE MRA can better visualize the bifurcations by rotation of the MIP volume and by correlation with MPR. In our study, the differences may also be due to different experience of the observers for the MR and DSA examinations. Thurnher et al. found that, even if measurements were performed carefully with a defined protocol, variability in measurements of AAA lengths at CE MRA and CTA is common (Thurnher et al. 1997).

Three out of the six diameter measurements were significantly smaller on MRI with CE MRA than on DSA and CT, while three showed no significant difference. The variations in diameter measurements on MRA-MIP with significant underestimation of D1 could be due to the observer dependent determination of the vessel boundaries (individual observer selection of window settings). It has been shown that vessel diameters have the tendency to be underestimated on MIP (Westenberg et al. 2000). The pair-wise differences with clinically unacceptable variations of measurement were larger for D2 than for D1. In our study 95% of the aneurysms did not have a clearly delineated non aneurysmal distal aorta and therefore D2 was open to individual interpretation. The method with the highest percentage of pair-wise differences with clinically unacceptable variations of measurement was CT, which can be explained by the thick transverse CT slices used in our study (Beebe 1997).

No significant differences were found between the observers. The method with the largest interobserver difference was CT, which is in agreement with a previous study where conventional CT measurements were subject to significant interobserver variability and that this variability was greater in transverse planes (Jaakola et al. 1996).

The comparisons between the MRA post processing techniques MIP and VRT showed significantly smaller diameter measurement for D1 on MIP, but no significant differences with regard to the D2 or lengths measurements. The VRT measurement of D1 is probably more accurate since vessel diameters are often underestimated on MIP (Westenberg et al. 2000). We chose to compare the MIP with a corresponding 2D image of VRT, and thus have not used the full 3D capacity of VRT. Measurements on 3D VRT should be more correct than MIP, since the measurements can be obtained in three dimensions and by using VRT in combination with surface enhancement, the boundaries between the contrast enhanced blood and the vessel walls may be visualized and the diameters will thereby be more accurately defined (Figure 8).

This study had some limitations. The patient material was rather small and we have no true reference measurement. Comparisons were made between analogue (DSA and CT) and digital measurements (MRI with CE MRA). The MR-measurements would most likely be more accurate if all studies had been obtained using the present MR-technique. CTA was not available at our centre why comparison with this method could not be performed.

Costs in follow-up of endovascularly repaired AAA—Paper IV

In this study, we found that MRI with CE MRA can be cost-effective for follow-up of endovascularly repaired AAA depending on the risk of contrast media induced nephropathy (CMIN) for CT with DSA, or CTA. MRI with CE MRA should be the method of choice for patients with pre-existing renal insufficiency.

In our study, three out of 23 patients (13%) had pre-existing renal insufficiency before endovascular repair. In a study by Prince et al., 43 consecutive patients underwent CE MRA before repair of AAA, 20 of these patients were at increased risk for exposure to iodinated contrast media (18 patients (42%) had pre-existing renal insufficiency and two had known major allergic reactions to iodinated contrast media) (Prince et al. 1995 J Vasc Surg).

Excluding the risk of CMIN, the cost of five years follow-up of MRI with CE MRA (5,715) is substantially higher than the cost of CT with DSA (3,095), and CTA (3,573). The risk calculation in our study identifies the critical risk of CMIN per CT with DSA, or CTA that would lead to equal costs for the five years follow-up. We found that if the critical risk (*r*)
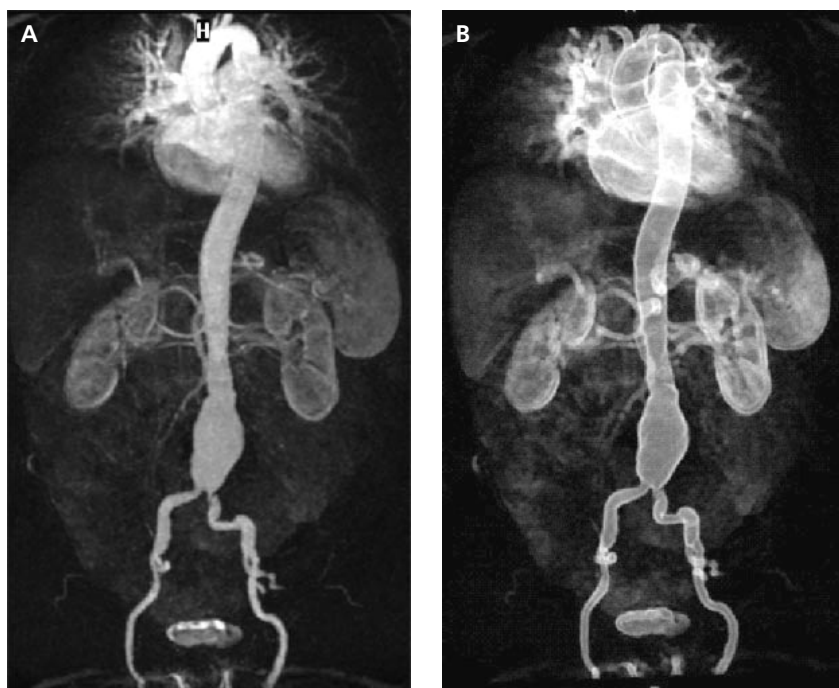
Figure 8 A–B. CE 3D MRA; MIP reconstruction (**A**) and VRT reconstruction (**B**), both in posterior-anterior projection.

of acquiring CMIN was 6% per examination with CT with DSA, and 5% per CTA examination, this would lead to equal costs with MRI with CE MRA during the five years follow-up. When taking into account the risk of CMIN per follow-up examination with CT with DSA, or CTA, the projected costs converge with the costs for MRI with CE MRA.

In view of the reported risk of CMIN for patients in general, 0–10% (Krause 1998) and with pre-existing renal insufficiency in particular, 12–27% (Morcos and Thomsen 2001) the risk for patients endovascularly repaired for AAA may well be higher than these estimated critical risk levels. To determine this, larger patient series than presented in this study are needed. It should be noted that in the expression (1) used to obtain this estimate, the costs are equated if only one single CMIN occurs during the follow-up. It is assumed that the risk of developing CMIN is independent of time and that this event could take place at any time during the follow-up. In a clinical setting, the patients at risk of CMIN may be likely to develop this early in the follow-up. This would then increase the risk of active treatment during consequent CT with DSA, or CTA examinations. The cost increase from this would then further favour MRI with CE MRA.

Using iodinated contrast media exposes the patients to a risk of allergy-like reactions, which exhibits an overall incidence of 1–2% (Krause 1998, Morcos and Thomsen 2001). The overall complication rate of femoral angiography is 1.7% (Hessel 1983). These adverse events also negatively influence the follow-up costs with CT with DSA, or CTA. We have not taken into account these possible cost increments in this study.

Mid-term results with the Stentor and Vanguard—Paper V

In this study, we found that complications in endovascularly repaired AAA with the Stentor and Vanguard were common. A secondary intervention was required in 60% of the patients. A summary of the outcomes for the patients is shown in Table 6.

In the EUROSTAR registry the incidence of endoleak varies from 10–44% (Cuypers et al. 1999). In our study endoleak was found in 15 out of 23 patients (65%). Seven of these patients had more than one endoleak. The high rate of secondary endoleak in our study is probably attributable to the Stentor and Vanguard stent-grafts. The high sensitivity of MRI with CE MRA to detect endoleak may also be attributable (Engellau et al. 1998, Haulon et al. 2001, Golzarian and Struyven 2001). We observed reduced incidences of endoleak

Table 6. Outcomes for 23 patients endovascularly repaired for AAA (Paper V)

Outcome	n	(%)
Endoleak	15	(65)
Graft migration	8	(35)
Graft deformation	18	(78)
Graft limb stenosis	2	(9)
Graft limb thrombosis	2	(9)
Graft frame fracture	1	(4)
Vertebral body infarction	2	(9)
Periaortic inflammation	2	(9)
Aortoenteric fistula	1	(4)
Secondary endovascular repair	7	(30)
Conversion to open repair	7	(30)

and secondary interventions in the patients included in the later part of this. This was probably a result of the technologic improvements to the Vanguard stent-graft, better implantation technique and more appropriate patient selection.

No changes of the aneurysm neck diameters were found. Earlier studies of aneurysm neck diameter changes have shown contradictory results (Malina et al. 1997, Matsumura et al. 1997, Prinssen et al. 2001). In our study, no significant changes of maximum outer aneurysm diameters were found in the group with endoleak or in the group without endoleak. This is not in agreement with previously published work where the aneurysm diameters increased in case of endoleak (Broeders et al. 1997, Malina et al. 1997, Matsumura et al. 1997). Explanations for these differences may be that our measurements were crude made with a ruler on films along the left-right axis to the vessel. Volume calculating with the MRA 3D post processing technique VRT would be a more accurate method to assess aneurysm expansion than simple diameter measurements. Patency of lumbar arteries was found in all patients.

Risberg et al described that a clear, highly viscous fluid was aspirated from the aneurysmal sac in four patients who had developed endotension (aneurysmal expansion after endovascular repair despite any demonstrable endoleak), supporting the diagnosis of aneurysm sac hygroma. The attenuation on computed tomography was significantly less in three of the four patients (Risberg et al. 2001). A possible method of diagnosing the presence of a hygroma and its change during follow-up would be MRI (Engellau et al. 1998). The presence of fluid in the aneurysmal sac would then be seen as high signal intensity on T2-weighted images. In our study no patient without endoleak had aneurysm expansion.

The Stentor and Vanguard had a design with a flexible frame with relatively thin nitinol wires. This insufficient longitudinal stability resulted in downward stent-graft migration (in our study 35% of the patients) and stent-graft deformation (78%). Migration and deformation resulted in complications such as graft limb stenosis and thrombosis (9% respectively) and fractures of the nitinol frame (4%). This was in accordance with previous studies (Becquemin et al 1999, Resch et al. 1999, White et al. 1999, Czermak et al. 2001). Although the present MR protocol is insufficient to exactly measure stent-graft migration (slice thickness 10 mm on T2-weighted transverse images) a migration during the follow-up can be noted.

Two patients had vertebral body infarction detected at 1 month follow-up which thereafter persisted. Both patients had clinical symptoms of microembolization to the spinal cord and/or the lumbosacral plexus with partial paresis of one leg. Full restitution was achieved in one patient, the other had persistent weakness of the leg.

Two patients had periaortic inflammation detected at 1 month follow-up with complete regression at 6 months follow-up. One of these patients was later found to have an aortoenteric fistula with ruptured graft fabric and was converted to emergency open surgery 18 months after the implantation (Norgren et al. 1998).

The complexity of the intramural thrombus organization over time is shown in Figure 7. In a complication free endovascularly repaired AAA the aneurysm sac thrombus became organized over time. However, in patients with endoleak and secondary interventions affecting the intramural thrombus, it either remained unorganized or partially organized, or changed from partially organized to unorganized or from organized to partially organized. The high signal intensity in the aneurysmal sac thrombus seen on T1- and T2-weighted transverse images in patients with unorganized or partially organized thrombus is consistent with hematoma (coagulated blood).

Graft frame fracture was found in one patient at four years follow-up on DSA. The Nitinol endoskeleton of the Stentor and Vanguard stent-grafts was held together with polypropylene sutures. When the sutures broke or became untied, the stent framework buckled, bringing its tips into contact with the overlying polyester cover. This resulted in graft erosion, type III endoleak, and aneurysm rupture. Causative factors were an unstable stent, movement between the tip of the stent and the overlying fabric, and a flimsy fabric (Chuter 2002). Neither the Stentor nor the Vanguard stent-graft is on the market due to reports on material breakdown (Uflacker and Robison 2000, Chuter 2002).

Clinical implementation

During the period of this study, the MR protocol has been changed due to improvements and developments of the MRA technique. Accumulating experience have had an impact on our follow-up routines of endovascularly repaired AAA. MRI with CE MRA replaced CT and DSA as the method for follow-up, since we found that MRI with CE MRA provided the relevant information. In addition, MRI was the sole method demonstrating intramural thrombus organization and vertebral body infarction. A spasmolyticum (Buscopan®) in combination with fasting was used to reduce bowel movement during the MRI with CE MRA examination. We ceased using these preparations since we found that the image quality was satisfactory without them. In addition, a known and observed side effect

of Buscopan is difficulty to micturate, and the majority of the endovascularly repaired AAA patients are elderly men.

In Paper II, MR velocity mapping did not provide additional information in follow-up of endovascularly repaired AAA. However, MR velocity mapping may be useful if suspected flow-related symptoms from the legs should occur after endovascular repair.

In Paper IV, we found that MRI with CE MRA can be cost-effective for follow-up of endovascularly repaired AAA depending on the risk of contrast media induced nephropathy for CT with DSA, and CTA. MRI with CE MRA should be the method of choice for patients with pre-existing renal insufficiency. When an imaging method with iodinated contrast media is being used, the patients should have their renal function checked with serum creatinine before the examination. Furthermore, administration of nephrotoxic drugs should be stopped at least 24 hours before contrast media administration. Patients with a known risk factor should also be followed with serum creatinine at 48 to 72 hours following iodinated contrast media administration (Murphy et al. 2000). It is also important that patients with renal failure are fully hydrated and given calcium-channel blockers before examinations (Sterner et al. 2000). The use of a non iodinated contrast media procedure, such as MRI with CE MRA should of course be preferred in these patients.

In Paper V, we found that complications with the Stentor and Vanguard stent-grafts were common and that a long-term follow-up of endovascularly repaired AAA is mandatory.

Conclusions and future aspects

In conclusion, we have found that:

- MRI with CE MRA provides the relevant information needed for follow-up of endovascularly repaired AAA. MRI was the sole method demonstrating intramural thrombus organization and vertebral body infarction (Paper I).

- MRI in a 1.5 T system may be performed safely in patients endovascularly repaired with the nitinol-supported stent-graft (Vanguard). MRI with CE MRA provides diagnostic image information with only minor metal artefacts. Image evaluation on CT can be disturbed at the graft limb junction and graft bifurcation by the beam hardening artefacts. MR velocity mapping did not provide additional information in follow-up of endovascularly repaired AAA (Paper II).

- The length measurements obtained with MRA-MIP were significantly shorter, but probably more correct, than those obtained with DSA. The diameter measurements obtained with MRI with CE MRA were more variable. Improvements of the CE MRA technique including VRT and a standardized determination of the vessel boundaries are needed for more reliable diameter measurements (Paper III).

- MRI with CE MRA can be cost-effective for follow-up of endovascularly repaired AAA depending on the risk of contrast media induced nephropathy for CT with DSA, or CTA. MRI with CE MRA should be the method of choice for patients with pre-existing renal insufficiency (Paper IV).

- Complications and secondary interventions were common in mid-term follow-up of patients endovascularly repaired with the Stentor and Vanguard. Long-term follow-up of endovascularly repaired AAA is mandatory (Paper V).

General conclusion

For MR-compatible stent-grafts, MRI with CE MRA could be the method of choice for follow-up of endovascularly repaired AAA. MRI with CE MRA should be the method of choice for patients with pre-existing renal insufficiency.

Future aspects

The future role of endovascular repair of AAA is still too early to predict but it is expected that especially high risk patients will benefit the most from this less invasive technique (Uflacker and Robison 2001, Chuter et al. 1999).

To improve the sealing of the stent-graft to the proximal aortic neck, new stent-graft designs have been developed that are anchored above the renal arteries with endograft fenestration to preserve renal and visceral vessel perfusion (Anderson et al. 2001). Another stent-graft design development is a branched stent-graft (Chuter unpublished results).

Improvements of the MR scanner with stronger and faster MR gradients and of the CE MRA technique regarding spatial resolution with maintenance of short acquisition times, will allow MRI with CE MRA to become a powerful modality for follow-up of endovascularly repaired AAA.

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