CT with 3D-Image Reconstructions in Preoperative Planning

ANGELIKI DIMOPOULOU
Computed tomography is one of the most evolving fields of modern radiology. The current CT applications permit among other things angiography, 3D image reconstructions, material decomposition and tissue characterization. CT is an important tool in the assessment of specific patient populations prior to an invasive or surgical procedure. The aim of this dissertation was to demonstrate the decisive role of CT with 3D image reconstructions in haemodialysis patients scheduled to undergo fistulography, in patients undergoing surgical breast reconstructions with a perforator flap and in patients with complicated renal calculi scheduled to undergo percutaneous nephrolithotomy (PNL).

CT Angiography with 3D image reconstructions was performed in 31 patients with failing arteriovenous fistulas and grafts, illustrating the vascular anatomy in a comprehensive manner in 93.5% of the evaluated segments and demonstrating a sensitivity of 95% compared to fistulography.

In 59 mastectomy patients scheduled to undergo reconstructive breast surgery with a deep inferior epigastric perforator flap, the preoperative planning with CT Angiography with 3D image reconstructions of the anterior abdominal wall providing details of its vascular supply, reduced surgery time significantly ($p < 0.001$) and resulted in fewer complications.

Dual Energy CT Urography with advanced image reconstructions in 31 patients with complicated renal calculi scheduled to undergo PNL, resulted in a new method of material characterisation (depicting renal calculi within excreted contrast) and in the possibility of reducing radiation dose by 28% by omitting the nonenhanced scanning phase. Detailed analysis of the changes renal calculi undergo when virtually reconstructed was performed and a comparison of renal calculi number, volume, height and attenuation between virtual nonenhanced and true nonenhanced images was undertaken. All parameters were significantly underestimated in the virtual nonenhanced images.

CT with 3D reconstructions is more than just “flashy images”. It is crucial in preoperative planning, optimizes various procedures and can reduce radiation dose.

Keywords: CT Angiography, 3D image reconstructions, haemodialysis, AVF/AVG, DIEP flap, surgery time, complicated renal calculi, PNL, true nonenhanced images, virtual nonenhanced images, CT Urography

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To my country and my family

“Ουκ ένι ιατρικήν ειδέναι, οστις μη οίδεν ό τι έστιν άνθρωπος”
Ιπποκράτης 460-377 π.Χ.

”You can not know medicine, if you do not know what human beings are”
Hippocrates 460-377 BC
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List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I. Angeliki Dimopoulou, Hans Raland, Björn Wikström and Anders Magnusson.
   MDCT angiography with 3D image reconstructions in the evaluation of failing arteriovenous fistulas and grafts in hemodialysis patients.
   Acta Radiologica 2011; 52: 935-942.

II. Jeroen M. Smit, Angeliki Dimopoulou, Anders G. Liss, Clark J. Zeebregts, Morten Kildal, Iain S. Whitaker, Anders Magnusson and Rafael Acosta.
   Preoperative CT angiography reduces surgery time in perforator flap reconstruction.

III. Angeliki Dimopoulou, Per-Erik Åslund and Anders Magnusson.
    A new technique for visualisation of complex renal calculi using Dual Energy CT and image merging, in the preoperative work-up of patients undergoing Percutaneous Nephrolithotripsy.
    Submitted

IV. Angeliki Dimopoulou, Lisa Wernroth and Anders Magnusson.
    Dual Energy CT in patients with complicated renal calculi undergoing Percutaneous Nephrolithotomy: virtual non-enhanced images vs. true non-enhanced images; correlation on calculi number, volume, size and attenuation.
    Submitted

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**Abbreviations**

2D two-dimensional  
3D three-dimensional  
AVF arteriovenous fistula  
AVG arteriovenous graft  
CT computed tomography  
CTA computed tomography angiography  
CTU computed tomography urography  
CVC central venous catheter  
DECT dual energy computed tomography  
DECTU dual energy computed tomography urography  
DIEP deep inferior epigastric artery perforator  
DLP dose-length product  
DSA digital subtraction angiography  
ESWL extracorporeal shock wave lithotripsy  
GEE generalised estimating equations  
HU Hounsfield unit  
KDOQI kidney disease outcomes quality initiative  
MIP maximum intensity projection  
MPR multiplanar reformation  
MRA magnetic resonance angiography  
NSF nephrogenic systemic fibrosis  
PACS picture archiving and communicating system  
PNL percutaneous nephrolithotomy  
PTA percutaneous transluminal angioplasty  
PTFE polytetrafluoroethylene  
ROI region of interest  
SD standard deviation  
SIEA superficial inferior epigastric artery  
SPSS statistical package for the social sciences  
SRR Swedish renal registry  
TNI true non-enhanced images  
TRAM transverse rectus abdominis musculocutaneous  
VNI virtual non-enhanced images  
VRT volume rendering technique
Introduction

The foundations for the present thesis were set unexpectedly one day in October 1999, when Prof. Anders Magnusson asked me “to look at a thing and put some numbers together”. Being fresh out of Med. School I was more than happy to look at that particular thing and put the numbers together, even if it never led to anything substantial. It also turned out that the numbers were wrong. Four years later, returning to the Department of Radiology at the University Hospital in Uppsala, it was my turn to ask him if there was any research project that I could embark on. Yes he answered. “I have several ideas about our haemodialysis patient population and a new CT method that we have begun with”. Work on this thesis started in November 2004, and is ending now eight years later.

The only familiar things left from the original research plan are Paper I and the notion “CT” (Computed Tomography). Everything else has been modified and changed throughout these years, often because of surprising and unforeseen events. The four papers that would cover different diagnostic aspects of vascular access pathology in the haemodialysis population shrunk to one; vascular access surgical procedure numbers declined for a long period of time and the emergence of Nephrogenic Systemic Fibrosis put a firm stop to any future contrast enhanced MR Angiography examinations in haemodialysis patients.

We were forced to change direction and adapt (according to the “sink or swim” principle) and find new hypothesis to explore. CT remained the one true red thread in this thesis, together with the belief that 3D image reconstructions are much more than just “fancy pictures in colour” to impress colleagues with. This thesis hopefully shows that they are a valuable tool, and if you try to understand how to best use them they might reward you by improving diagnosis and future treatment for your patients.
Background

On Computed Tomography

There is unfortunately not enough space in this thesis for a detailed analysis of CT and image reconstruction principles. CT is probably one of the most important innovations of radiology and medical imaging. Some of the mathematical theory behind it was described in 1917 by Johann Radon in the “Radon Transform” and was later amplified and supplemented by other researchers. The 1960s was an important decade; William Oldendorf built a prototype of an X-ray source linked together with a detector, which could rotate around an object. His article describing the prototype was published in 1961 and partly based on it could Allen M. Cormack develop the mathematical principles of image reconstruction, published in 1963 and 1964.

The biggest breakthrough came in 1972 when an unknown engineer from EMI (the well-known record company), named Godfrey Hounsfield, gave a lecture entitled “Computerised Axial Tomography - a new means of demonstrating some of the soft tissue structures of the brain without the use of contrast media”. The first clinical patient scanned, underwent a brain CT on October 1971 in London. The first body CT scanning was performed on Hounsfield himself on December 1974.

Hounsfield and Cormack shared the Nobel Prize for Physiology or Medicine in 1979 and the name of Hounsfield became immortalized with the every-day use of the term “Hounsfield Units”, (defined as the x-ray attenuation of different materials in CT and displayed in shades of gray). CT is now one of the pillars of modern Radiology.

The working principle of CT is an x-ray source rotating around an object. The source emits x-ray beams that pass through a thin section of the object and are received by detectors placed on the opposite side of the x-ray source. The detectors measure the intensity of the radiation that has passed through the object and image reconstruction in a mathematical way is achieved with the help of the inverse Radon transformation, where attenuation within every point of the scanned section is calculated. The image reconstruction will eventually yield slices of the examined volume in shades of grey that appear on computer screens or are printed on films.

The technology of CT machines is constantly evolving. Sequential imaging (scanning one slice of the object at a time, section-by-section) is a thing of the past. Spiral CT appeared in 1989 and was based on scanners with a continuously rotating x-ray tube. A helix of raw data was produced from which axial images had to be generated. The object scanned was seen more as “volume” than individual “slices”. Resolution improved and due to the short scan time, it became possible to complete an examina-
tion during a single breath hold. Additionally, imaging during the arterial phase was achieved with spiral CT and CT Angiography (the possibility of scanning and capturing arterial enhancement in image) became a reality in 1991. With multislice (or multidetector) CT appearing in 1998 and with the increasing number of detector arrays, even more possibilities in imaging were suddenly available: increased scan speed, shorter scan times, increase of scan length, thinner sections and near isotropic (identical values in each direction) imaging. The object scanned was now a volume with three dimensions and could be viewed from every angle. Thus the “voxel” (volume element) became an everyday term. Temporal and spatial resolution was improved, but image reconstruction became much more complicated with the rising number of detectors, and the raw data produced needed to be interpolated in more advanced ways (e.g. cone beam interpolation, z-filtering, image noise). In 2004 a 64-slice CT became commercially available, followed by the dual source CT in 2006, the 256-slice CT in 2007 and the new dual source 128-slice CT in 2009.

All these innovations are not without costs: the augmented use of CT and the technological advances have led to increasing radiation dose to patients and to an enormous amount of data generated and needing to be archived.

**On image reconstructions**

The cornerstone of successful image reconstruction is isotropic or near-isotropic imaging. There are two-dimensional (2D) and three-dimensional (3D) post-processing techniques and emphasis will be given in this thesis to multiplanar reformations (MPR), maximum intensity projections (MIP) and volume rendering techniques (VRT). There are dedicated and vendor specific workstations equipped with commercially available software where image reconstruction can take place.

MPR is the simplest method of reconstruction. A volume is built by “stacking” the axial slices one on top of the other. The post-processing software can then cut slices through this volume, e.g. in the coronal or the sagittal plane. The result is a 2D rendering of the volume by depicting the voxels that are placed one on top of the other in the plane of choice, and consequently MPR reconstructions usually have the width of a voxel. Due to the fact that the entire volume data is available, modern post-processing software can also reconstruct in oblique planes and follow curving structures (e.g. vessels), allowing the entire chosen length of the vessel to appear in one image. By using “thick” MPR (with section
thickness greater than one voxel, and preferably several mm) image noise can be minimized and image quality improved. MPR reconstructions are superb in providing anatomical orientation and illuminating the relationship between organs and structures in multiple anatomical planes (Figure 1).

MIP reconstructions enhance areas of “maximum intensity”: a view plane is chosen through the part of the examined volume that is of interest, and the voxels with maximum CT numbers (highest attenuation) in this particular view plane are displayed. MIP mode reconstructions can be performed either for an entire volume or for a chosen section. MIPs are mostly used to depict vessels containing contrast material in CT Angiography (CTA) taking advantage of the attenuation difference between intensively enhancing vessels and non-enhancing background. Provided there is a prominent difference in the attenuation of the contrast enhanced vessel and calcified plaques located on the vessel wall, they can be visibly differentiated in MIP. A problem can arise when vessels and bony structures are superimposed (since calcium has high attenuation) and bony structures often need to be segmented and removed from the volume of interest by dedicated segmentation software (Figure 2a and 2b). The same applies for contrast enhancing parenchymal organs.

Figure 1.
MPR reconstructions of the left arm of a haemodialysis patient. An arteriovenous fistula is present in the forearm (not visible) and the patient is examined with a CTA.
**Figure 2a.**  
MIP reconstructions of the same patient as in figure 1. The head, neck, left shoulder and upper arm are shown. All contrast-enhanced vessels are prominent but so are skeletal structures.

**Figure 2b.**  
The same image as figure 2a, but after bone segmentation. Skeletal structures are now removed and assessment of vessels is easier. Note the visible calcifications of the brachial artery.
VRT is a rather complicated reconstruction process. A two-dimensional representation from a three-dimensional dataset (the examined volume) is achieved by assigning colour and opacity values to every voxel of the dataset. Brightness and reflection are also part of this complicated reconstruction process. By using the colour look-up table (CLUT), which is common in all VRT software, colour and opacity are assigned to various tissues based on their CT numbers (Figure 3a). In the CLUT, a number of trapezoids can be chosen, representing the attenuation ranges of relevant tissues/materials: air, fat, bone, parenchymal organs, contrast-enhanced vessels. These trapezoids can be colour-coded, and the tissues/materials they represent will appear in the same colour in the final images. There is a risk of attenuation overlap between the various tissues/materials and therefore the trapezoids can also overlap in the CLUT, resulting in erroneous tissue overlap in the final images. There is also a risk that pertinent information included in the examined volume is not displayed, since the programme is to a great degree interactive, and the evaluator can choose which tissues/materials are to be depicted. Changes in opacity are also a potential pitfall: opacity varies from 0% (totally transparent) to 100% (totally opaque) and has default settings in the post-processing programme but can also be manipulated manually. VRT images can be reconstructed from practically all CT examined parts of the body, but they have perhaps had the greatest impact in CTA. Vessel calcifications can be rendered in a different colour than vessel contents and enhancing parenchymal organs can be depicted with great detail. Skin contours and even patient clothing can be reconstructed and visualised (Figure 3b), a fact that proved very useful in the second paper of this thesis.
Figure 3a.
Figure 2a in the VRT mode. Parenchymal organs (heart, thyroid gland) are visible as well as contrast enhanced vessels. This programme also allows bone segmentation. Note the “stenosis” in one of upper arm veins (visible also in figure 2a and 2b).

Figure 3b.
The exact image as 2a and 3a, but with reconstructed patient skin and patient shirt. It is in all probability the shirt that is pressing on the soft tissues of the upper arm, causing the venous “stenosis”.
On Dual Energy CT

In order to achieve spectral CT imaging (spectral: information of the same view field captured at different wavelengths or wavebands) there are three prerequisites: two separate x-ray sources emitting different photon energies, a detector that can differentiate between these two photon energies and adequate difference of the spectral properties of the object imaged. For diagnostic radiology, the available x-ray tube voltages lie between 80 and 140 kV. For values lower than 80 kV the human body absorbs too many quanta, and for values over 140 kV the soft tissue contrast is too low to generate a diagnostic image. Regarding the spectral properties of the studied object, it is materials with sufficient differences in their atomic numbers (Z: the number of protons in the atomic core) that can be adequately differentiated. Materials with similar atomic numbers will demonstrate similar attenuation characteristics over the CT energy range. The human body consists mostly of materials with low atomic numbers, e.g. hydrogen (Z= 1), oxygen (Z= 8), with an exception being calcium (Z=20). Iodine, which is widely used as a contrast material in CT, has an even higher atomic number (Z=53) and so can be well differentiated from other body tissues.

The idea of incorporating dual energy CT in clinical practice was described in the 1970s and the 1980s. Chiro et al in their article from 1979 came to the conclusion that “dual-energy CT can provide clinically useful tissue signatures”. Kalender et al in their article from 1986, studied material decomposition in a prototype CT with rapid kVp switching: tube voltage was switched between high and low kVp values which allowed simultaneous acquisitions of dual-kVp data in one scan.

Scanner technology was at that time not advanced enough to perform dual energy scanning in a practical and safe way. Long scan times, motion artefacts, post-processing difficulties and limited spatial resolution kept dual energy CT outside the clinical routine until 2006.

The above-mentioned problems are now solved and there are three ways the modern dual-energy CT can operate: the dual source CT with two different x-ray sources running at different tube voltages and two different detectors, the rapid kVp switching, and the layer detector technology. The dual energy CT used in this thesis is the dual source (Somatom Definition, Siemens Healthcare). Two separate CT acquisition systems are mounted orthogonally in one gantry and rotate around the patient simultaneously. They have their own tubes, generators and detectors, whereas they share a common image reconstruction system. In Somatom Definition both detectors are of the 64-slice design, but detec-
tor A has a field of view of 50 cm and detector B a field of view of 26.8 cm. Both tubes can be operated independently concerning voltage and current settings, but the standard voltage is 140 kV for tube A and 80 kV for tube B. There are three ways to operate the dual source CT and for papers III and IV of this thesis the dual-energy scanning mode was used.

Materials that can be scanned simultaneously with two different x-ray spectra yield information on their chemical composition and material decomposition becomes possible. The early applications of dual source CT included bone removal, the virtual subtraction of iodine from contrast-enhanced images, the virtual removal of calcified plaques from a contrast-enhanced vessel and the chemical characterization of urinary calculi. The image reconstruction is based on the “three material decomposition principle” where every voxel in the common scan field of detector A and B is theoretically composed by triplets of materials e.g.: fat, soft tissue and iodine or soft tissue, bone and iodine. By scanning the same voxel with 140 kV and subsequently with 80 kV two different attenuation values will be produced. It is the difference between these two attenuation values that determines the dual energy characteristics of the material and allows for differentiation. Each dual energy acquisition will generate the following data sets: pure 80 kV, pure 140 kV, and linearly weighted average data similar to a 120 kV dataset using 70% information from Tube A and 30% from tube B.

In Somatom Definition, the restricted field of view for detector B will result in dual-energy scanning only for the area that is covered by both detector A and B. That particular problem is near its solution with the next generation of dual source CT (e.g. Somatom Definition Flash) where detector B has a larger field of view (33 cm). Regarding the question of radiation dose to patients, the dual source CT has a dose modulation system (CareDOSE4D), which adapts tube current to patient anatomy. Dual source scanning will not require a higher patient radiation dose than an average single source CT. The next generation dual source (Somatom Definition Flash) is equipped with an additional tin filter in the high energy tube that can increase the spectral separation of the low and high energy spectrum resulting in even better material characterization, but which can also narrow the 140 kV spectrum, filtering unnecessary photons and resulting in better dose efficiency. In the future, there might come a time when there are monochromatic x-ray tubes for diagnostic purposes, imparting no radiation dose to patients.
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Paper I

According to the Swedish Renal Registry (SRR) report for 2011, a total of 8501 patients with renal failure were “in treatment” by December 31\textsuperscript{st} 2010, in Sweden. Of these, 4 740 (55.7%) had a functional renal transplant, 2 920 (32%) were receiving haemodialysis, and 841 (12.3%) peritoneal dialysis\textsuperscript{13}. The primary cause of renal failure was glomerulonephritis, and diabetes came in second place. The annual mortality of this patient population was high: 25.7% for haemodialysis patients and 2.7% for renal transplant patients.

Vascular access is of paramount importance to the haemodialysis patient population. A functioning arteriovenous fistula (AVF) is considered the method of choice for haemodialysis, followed by arteriovenous grafts (AVG). The third alternative, which is the central venous catheter (CVC), is closely related to increased mortality and morbidity\textsuperscript{13,14} and should be avoided when possible.

Since the numbers of AVF and AVG decreased in the mid 2000:s, the National Kidney Foundation together with the Kidney Disease Outcomes Quality Initiative (KDOQI), launched the ”Fistula first” programme in 2006\textsuperscript{15} to increase the use of AVF in the United States.

Of the various anatomical combinations of arteriovenous fistulas (Figure 4), the radiocephalic fistula is the most preferable, followed by the brachiocephalic, the transposed brachiobasilic and lastly the AVG\textsuperscript{15}.

The radiocephalic fistula which, as the name describes, is the surgically created anastomosis between the radial artery and the cephalic vein at the level of the wrist was first described by Brescia and Cimino in 1966\textsuperscript{16}.
Figure 4.
The various anatomical combinations in AVF creation in the upper extremity.
Since then it has been considered the cornerstone of haemodialysis vascular access: it has a distal location in the upper extremity, it is easy to create surgically, easy to use and has been proven to have the best patency (lowest rate of thrombosis and infection, fewest required interventions, longest survival)\textsuperscript{15}.

The AVG comprises of a tube of synthetic material, usually polytetrafluoroethylene (PTFE), which is anastomosed to an artery and a vein. There are looped and straight varieties (Figure 5), the looped being preferable. They are easy to cannulate, offering a large surface area, and

\textbf{Figure 5.}

Schematic images of a straight and a looped AVG in a forearm.
there are multiple insertion sites available. Their expected patency is between three to five years. The main complication of AVF and AVG is failure, which is associated with significant morbidity and mortality. The predominant cause of failure is stenosis, leading to thrombosis. According to some materials, more than 80% of vascular access failure is due to unresolved thrombotic episodes, whereas the remaining 20% is due to secondary infections, aneurysms and steal. The areas of stenosis usually occur in the venous circulation, near the vein/artery and the vein/graft anastomosis (Figure 6), whereas pure arterial stenoses represent less than 2% of vascular access failures. Stenoses

![Figure 6.](image)

An angiographic image of an AVF in a forearm with a stenosis on the venous side, just proximal to the arteriovenous anastomosis.
have a tendency to occur in areas of turbulent flow and in the presence of intimal stress and injury. These locations will be more susceptible to vascular inflammatory response, resulting in smooth muscle hyperplasia and the gradual formation of a local stenosis. Therefore endothelial and neointimal hyperplasia is the primary reason for the formation of stenosis 18,19.

Continuous surveillance of AVF and AVG is mandatory to ensure adequate function.

With prospective and systematic monitoring the stenoses that seem to develop in the great majority of vascular accesses can be detected and corrected in time and the rate of thrombosis can thus be reduced 14,15,18,20. There are several ways to monitor vascular access: physical examination, sequential access flow measurements, sequential static and dynamic pressure and recirculation measurements, the rationale being that a point where action should be taken can be detected on time. All of these can be applied in the haemodialysis wards and the haemodialysis machines measure both flow and pressure. The saline ultrasound dilution technique (Transonics Hemodialysis Monitor, Transonics Systems Incorporated, Ithaca, NY, USA) is currently the best available monitoring device. It measures both blood flows through the vascular access and recirculation percentage 15,17, and is used monthly on all patients in our clinic. When cannulating difficulties occur, abnormal findings are noted during physical examination (aneurysms, cessation of bruit in the access), blood flow rates fall below 400-500 mL/min in AVF and 600 mL/min in AVG, elevation of static and dynamic venous pressures occur, and recirculation percentages rise, it is time to refer the patient for further diagnostic work-up and imaging.

A well-established and non-invasive method for AVF and AVG examination is ultrasound. It is also inexpensive and easy to use. A number of reports using ultrasound as a screening or diagnostic tool in vascular access dysfunction appeared in the 1990s, and the use of Colour Doppler consolidated the method 21-23. It was also established that Colour Doppler could detect high-grade stenoses and could predict thrombotic events and failure both in AVF and AVG 21,23, as well as reduce the number of
the more invasive fistulographies. However, Colour Doppler ultrasound is operator depended, and requires accurate measurements of the cross-sectional area of the access. Errors can be caused by variation of the cross-sectional areas and the angle of the ultrasound examination\textsuperscript{15} and the method cannot provide a complete vascular mapping of the upper extremity and of the central vessels.

The “gold standard” in AVF and AVG imaging has been digital subtraction angiography (DSA), which also offers the possibility of therapeutic intervention. Initial reports of DSA applied in the context of AVF and AVG examination were published in the mid 1980s\textsuperscript{24,25} and since then it has been the method of choice in imaging failing AVF and AVG\textsuperscript{14,15,18,20}. DSA offers a complete mapping of the AVF/AVG and of the surrounding vascular tree, including the central vessels. Pathological changes, usually stenoses, can both be diagnosed and treated by percutaneous transluminal angioplasty (PTA) during the same session. Stenoses are graded by the percentage of narrowing of the vessel, compared to the diameter of a “normal vessel” directly upstream or downstream. Stenoses > 50% of “normal vessel” diameter are considered significant. DSA is however an invasive procedure with potential complications. At best, one puncture of the AVF/AVG or surrounding vessels is necessary and iodinated contrast medium has to be given, usually repeatedly. The available equipment is not designed for imaging vascular constructions of varying anatomy in the upper extremities and can be cumbersome to use. The anatomy is not always obvious and a second puncture may be needed to clarify the pathology and access it for PTA.

Therefore, there have been a growing need for a non-invasive, simple and accurate method that could depict AVF/AVG anatomy, pinpoint the pathology and provide a complete vascular map that could be used in a subsequent DSA/PTA examination. The use of computed tomography angiography (CTA) in the imaging of failing AVF/AVG was initially described in 1998\textsuperscript{26}. A number of publications followed\textsuperscript{27-31} and the method has been gaining in popularity ever since, much due to the possibility of 3D image reconstructions that interpret the axial images in a new way.
Breast reconstructions with autologous tissue in post-mastectomy patients have been steadily gaining in popularity during the past decade. The use of free flaps has been gradually increasing, particularly the use of deep inferior epigastric artery perforator flap (DIEP) and the superficial inferior epigastric artery perforator flap (SIEA). They have been successively replacing the traditional transverse rectus abdominis musculocutaneous flaps (TRAM) and implants/tissue expanders. Free flaps of the DIEP and SIEA type have now become the optimal standard of care after mastectomy. There are obvious advantages of free flaps compared to foreign materials. The skin and subcutaneous fat of the lower abdomen can be formed to anatomically resemble a natural breast and the long term results compared to tissue expanders are superior regarding rate of complications, form and patient satisfaction.

There is a variety of flaps that can be harvested from the abdominal wall. The pedicled TRAM flap (Figure 7) includes the entire rectus abdominis muscle (unilateral or bilateral) as a “carrier” for the skin and subcutaneous tissue of the lower abdomen. The muscle is tunnelled under the abdominal skin and transfers the flap to the chest wall, where the new breast is formed.

A variation of the TRAM flap is the free TRAM (Figure 8) where a smaller portion of the rectus abdominis muscle is elevated, and the vessels supplying the flap are anastomosed to vessels on the receiving site.

Both these techniques involve a varying amount of muscle and fascia and consequently there is a higher incidence of abdominal wall complications such as asymmetry, bulging and hernias. The most serious complication of flap surgery is flap morbidity, often due to compromised perfusion. Symptoms can include total or partial flap loss, fat necrosis and venous congestion.

The concept of muscle sparing technique was taken a step further when the first DIEP flap for breast reconstruction was successfully performed in 1992. The DIEP flap utilizes the same adipocutaneous tissue from the lower abdomen as the TRAM flaps do, sparing the rectus abdominis muscle and fascia. For vascular supply, it is based on the inferior epigastric artery and vein and their perforators through the rectus muscle. The inferior epigastric artery (Figure 9a and b) arises from the external iliac artery and courses in a caudo-cranial direction along the posterior fascia of the rectus muscle. According to the classification of Moon and Taylor, approximately 57% of inferior epigastric arteries have a double-branched system (Type II) whereas 29% have a single trunk (Type I). The remaining 14% (Type III) divide into three or more branches. Two rows of smaller perforating arteries (lateral and medial) go through the rectus muscle on each side to supply the adipocutaneous tissue above.
Figure 7.
Schematic drawing of the pedicled TRAM flap.

Figure 8.
Schematic drawing of the free TRAM flap.
Figure 9a.
The course of the inferior epigastric artery.
Figure 9b.
Inferior epigastric arteries arising from the external iliac arteries. MIP reconstruction of a CTA of the abdomen.
During the harvest of a DIEP/SIEA flap, dissection starts from the lateral aspect of the lower abdomen gradually advancing towards the midline. The superficial inferior epigastric artery can be examined first, however in 90% of patients it is either non-existent or insufficient in size and diameter. On the other hand, a rather large superficial inferior epigastric vein is a common finding and is kept as a back up if an additional venous pedicle is needed. When the superficial artery is deemed inadequate the deep inferior epigastric system is examined instead.

The lateral perforator row is dissected first and a dominant perforator is sought. If none is located the dissection continues to the medial row and a dominant perforator is sought there. The flap can be based on one perforator if the vessel calibre is around 1.5 mm. The sheath of the rectus muscle and muscle fibres are carefully dissected around the perforator vessels towards the deep inferior epigastric artery. When a sufficiently long pedicle is produced (approximately 10 cm) the DIEP flap is lifted and transferred to the chest wall (Figure 10). The receiving site has already been surgically prepared and microvascular anastomoses are performed, preferably to the internal mammary artery and vein or the thoracodorsal vessels. It is of paramount importance at this stage that the vascular pedicles of the flap are not twisted or kinked. DIEP and SIEA flaps result in very low abdominal wall morbidity since they reduce damage to the rectus muscle and sheath to a minimum.

The success of free flap surgery is very much dependent on detailed knowledge of the vascular supply of the anterior aspect of the lower abdomen. Flap surgery is a complex and time-consuming operation so

Figure 10.
Schematic drawing of a DIEP flap.
meticulous preoperative planning, finding and identifying vessels that will supply the flap will facilitate flap design and survival. However each patient has an individual vascular architecture, so the variations of vessel anatomy are infinite. Traditionally, ultrasound has been the most common imaging technique used in the preoperative work-up. Unidirectional Doppler ultrasound (acoustic Doppler) is the most common instrument used for such an assessment. Ubiquitous, handy, easy to use, inexpensive and with a short learning curve it has been shown to be too sensitive, and false positive findings are common. It reacts even at small calibre vessels that will not provide adequate blood supply to a flap, and has difficulty distinguishing perforators from axial vessels. There are also concerns about the specificity as patent vessels can be overlooked because of larger vessels in the vicinity or background noise. Additionally, the examination cannot be reproduced and generates no image for future use.

Colour Doppler ultrasound offers a series of advantages and a larger amount of information about calibre and course. The perforators can be traced to their source and visualisation of main axial vessels is also feasible. Velocity measurements can be made and flow direction is established. High frequency transducers can also assess superficial vessels with ease. Although sensitivity is very high, specificity is low since only a small area can be examined at any time. An experienced technician or doctor with knowledge of perforator flap surgery needs to perform the examinations. Still images and film clips can be generated but in general the examination is not reproducible for the surgeon.

In 2006 the first publications of preoperative planning of perforator flaps with the use of multidetector-row computed tomography (MDCT) appeared. The concept of imaging the deep inferior epigastric arterial system perforators and adjacent veins with CTA and producing 3D image reconstructions which localize and mark perforators in such a way that the surgeons revise the material in the operating room was presented for the first time in 2006. Alonso-Burgos et al described CTA of the lower abdominal wall in a pilot study with six patients and Masia et al, using approximately the same principles and technique, published material with 66 patients.

Preoperative CTA of the lower abdomen in patients planned for perforator flap surgery was introduced to our clinic in March 2006.
Urolithiasis is a common condition in the Western world. The lifetime risk of urinary calculi formation in the United States is approximately 12% for males and 6% for females. It remains a cause of significant morbidity despite technological advantages, and its prevalence in the Western world is rising. Well-known risk factors for calculi formation include male sex and family history. There are also however dietary, metabolic and infectious reasons that promote or facilitate calculi formation.

In terms of chemical composition there are several types of urinary calculi. The most common type accounting for approximately 80% is composed of calcium salts (oxalate, phosphate). Uric acid accounts for 10% and the remainder are struvite and cysteine calculi. With the exception of uric acid calculi, the majority are radiopaque. They are therefore easily visualized by CT, which has become the imaging method of choice for their detection. Most patients suffering from urolithiasis have small calculi and spontaneous passage is common for sizes up to 4-5 mm. Symptomatic patients who require treatment are usually subjected to extracorporeal shock wave lithotripsy (ESWL), where calculi are fragmented or even pulverized by shock waves.

There is however a minority of patients suffering from large, complicated or recurrent calculi. This category includes patients with staghorn calculi and in such cases treatment with ESWL is usually inadequate. A different approach is needed to render these patients stone free.

In 1976 Fernström and Johansson described a procedure named “percutaneous pyelolithotomy”. This was an extraction technique, where renal calculi could be removed through a percutaneous nephrostomy channel under radiological control. Now known under the term “percutaneous nephrolithotomy” (PNL), it plays a dominant role in the treatment of staghorn or complicated upper urinary track calculi.

According to the European Association of Urology guidelines, PNL is indicated for renal calculi that exceed 20 mm in diameter, or calculi larger than 15 mm located in a lower calyx, particularly when narrow infundibula are present. It is also the first-line treatment in patients with renal calculi and concurrent anatomical anomalies (crossed, fused, horseshoe or ectopic kidneys), as other treatment options do not meet with satisfactory stone-free rates and PNL is preferable to open surgery.

PNL is a minimally invasive procedure performed by urologists. Depending on the location of the calculi the best possible approach (optimal tract) is decided beforehand and during the procedure the urologist following the optimal tract, enters the renal collecting system percutaneously with a nephroscope, and either removes or pulverizes the calculi. PNL success rates in clearing calculi burden vary between 80% and 90%.
depending on various authors. Essential for success and safety during PNL is accurate preoperative imaging and image guidance during the procedure. CT urography (CTU) with non-enhanced and excretory series, and 3D image reconstructions is now considered the method of choice for preoperative access planning.

A CTU demonstrates the exact location of calculi and the anatomical and spatial relationships between calculi, collecting system and adjacent organs. Use of the CTU enables the choice of optimal percutaneous access thus removing the largest possible calculi burden with minimal morbidity. The upper renal pole approach (puncture of an upper calyx) is often very successful in clearing stone burden but seems to be associated with a greater number of complications.

However, not every CTU examination is successful in the preoperative planning and determination of optimal tract. Patient respiration and motion between the non-enhanced and excretory series may result in discrepancies in kidney and calculi positions, making the planning more challenging. There is also the risk of attenuation overlap of calculi and of the excreted contrast material, which can result in calculi being masked by contrast. It is therefore of primary interest that the excreted contrast in the renal pelvis does not form dense “pools”, obscuring calculi or resulting in erroneous size measurements. Studies indicate that calculi attenuation ranges between 250 and 1600 HU and according to the study of Patel et al, the density of the excreted renal contrast in a renal collecting system will range between 200-300 HU. The overlapping attenuation can result in contrast obscuring calculi (Figure 11). An image reconstruction method that can render calculi visible within contrast, or virtually subtract contrast leaving visible calculi of accurate size and shape is therefore of interest.

With Dual Energy CT (DECT) being made available in clinical practice in 2006 material characterization has become feasible. Iodine has ideal dual energy properties and the possibilities of iodine differentiation were explored at an early stage. Numerous publications describing the virtual subtraction of iodine from contrast enhanced images and the construction of virtual non-enhanced images (VNI) and their comparison with true non-enhanced images (TNI) in various clinical fields appeared. Urinary calculi were an early point of interest of DECT applications. Thus, calculi material characterization (differentiating chemical components e.g. calcium from uric acid) is now established and widely used, and there are recent studies concerning the detectability of urinary calculi in VNI. However and to our knowledge, there are no publications of DECT Urography (DECTU) and VNI in patients with complicated
renal calculi. The term complicated includes large calculi (> 2 cm), calculi isolated in calyces with narrow infundibula, calculi in patients with concurrent anatomical anomalies, multiple calculi spread throughout a collecting system, and any calculus burden that cannot be eliminated without an invasive procedure.

Figure 11.
CTU examination of a patient with a staghorn calculus in the right kidney. To the left, the non-enhanced images where the staghorn calculus is clearly visible. To the right, the excretory images where calculus and contrast densities overlap. The calculus is totally obscured by the contrast.
Aims

General aim
The general aim of this thesis was to prove the usefulness and impact of CT with 3D image reconstructions in the preoperative work-up and planning of three different patient populations scheduled to undergo invasive or operative procedures.

Paper I
To illustrate the usefulness of CTA with 3D image reconstructions in the evaluation of haemodialysis patients with dysfunctional AVF and AVG and as a tool in planning future intervention.

Paper II
To establish if preoperative CTA of the lower abdominal wall in patients undergoing perforator flap surgery reduces operative time and the rate of complications.

Paper III
To develop and evaluate a technique improving material characterization in patients with complicated renal calculi examined with dual energy CT urography prior to percutaneous nephrolithotomy.

Paper IV
To create virtual non-enhanced images and compare them to true non-enhanced images in patients with complicated renal calculi examined with dual energy CT urography, prior to a percutaneous nephrolithotomy. The comparison was in respect to number, volume, size and attenuation of calculi.
Patients and Methods

Paper I

Patient data
Thirty-one patients with dysfunctioning AVF/AVG examined with a CTA from April 2003 to September 2004 were included in the study. Patient referrals to the Radiology department were because of AVF or AVG dysfunction. Details are shown on table 1.

Dysfunction consisted of any of the following: declining blood flow measured by Transonic ultrasound technique (n = 21), puncture and cannulating difficulties (n = 3), suspected occlusion (n = 2), aneurysm formation and prolonged bleeding (n = 2), elevated blood flows and extensive collateral venous network (n = 1), high percentage of recirculation (n = 1) and a swollen extremity (n = 1). Several patients were referred with a combination of two or more of the above-mentioned symptoms; the most prominent symptom was then selected.

The study was approved by the Institutional Ethics Committee. Permission was given to review and analyse the CTA and fistulography examinations, with waiver of informed consent.

Table 1.
Patient and access data.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Mean age</td>
<td>69 years (range 22 - 85 years)</td>
</tr>
<tr>
<td>Gender</td>
<td>23 men</td>
</tr>
<tr>
<td></td>
<td>8 women</td>
</tr>
<tr>
<td>Access type</td>
<td>24 AVF</td>
</tr>
<tr>
<td></td>
<td>7 AVG (4 looped, 3 straight)</td>
</tr>
<tr>
<td>Access location</td>
<td>30 forearm</td>
</tr>
<tr>
<td></td>
<td>1 upper arm</td>
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</tbody>
</table>
CTA Imaging
The examinations were performed on a Siemens Somatom Sensation 16 scanner. All patients were examined prone with the AVF/AVG arm extended above the head and placed in a vacuum mattress in order to minimise motion artefacts. An 18- or 20-gauge intravenous catheter was inserted in an antecubital vein in the contralateral arm and 100 mL of low-osmolar, non-ionic, iodinated contrast medium, were administered by a power injector with an injection rate of 3 mL/s, chased by a 40 mL bolus of saline. Bolus tracking was performed with a region of interest (ROI) on the ascending aorta and scanning was initiated approximately 10 sec after the trigger level of 150 Hounsfield Units (HU) was reached. The area covered was from the heart to the AVF/AVG hand in a caudo-cranial direction. Images were acquired during a single arterial phase and were reconstructed at a 1 mm slice thickness with a 0.7 mm increment.

3D Image post processing and data analysis
The original set of images was post processed and reformatted on commercially available software (Leonardo, Siemens Forchheim Germany). The Inspace programme of the software was used and, for each patient, the examined area was divided in three segments: forearm, upper arm and centre. Each segment was reconstructed separately so as to achieve the best possible image resolution, and VRT and MIP reconstructions were performed. Bone segmentation was routinely performed for all central segments. Two radiologists in consensus reviewed the images and the following parameters were noted and graded: comprehension of the anatomy of the AVF/AVG and the whole vascular tree to the heart (graded in a three-point scale: 1= poor, 2= average, 3= good), quality of contrast enhancement of AVF/AVG and other vessels (graded in a similar three-point scale as above). Measurements of AVF/AVG diameter and of “normal” principal vessels diameters were performed using the electronic measurement tool of the software, and significant stenoses (luminal reduction ≥ 50%) were noted. The presence of artifacts, aneurysms, occluded vessels and other abnormalities was noted.

Fistulography technique
The fistulographies were performed on a Multistar Time Operation Performance Plus system (Siemens, Forchheim, Germany) by two experienced radiologists. The CTA images were reviewed prior to fistulography and the procedure was designed accordingly. Direct retrograde punctures of the AVF/AVG were performed in almost all cases, with occasional punctures of the radial artery or an efferent vein in the upper arm. Punctures were performed either by free hand or with ultrasound guidance.
and a micropuncture set was used to gain access to the vessel. A standard 6F introducer sheath was then used for angiography with manual injection of low osmolar, non-ionic, iodinated contrast medium and images of the entire AVF/AVG and adjacent vascularity were obtained.

**Fistulography image analysis**

The presence of pathologic changes in the AVF/AVG or adjacent vessels was noted. Significant stenoses were treated with PTA during the same session. The DSA images were stored at the picture archiving and communication system (PACS) and reviewed by the same radiologists that had performed the 3D image reconstructions. Vessel anatomy, the presence, localisation, diameter and length of stenoses were noted. Measurements of AVF/AVG diameters had in most cases been performed during fistulography, but were reassessed and supplemented with measurements of “normal” principal vessels diameters, using the electronic measurement tool of the PACS software. The images with the highest degree of similarity to the 3D-CTA reconstructions were used for measurements. Subjective correlation of the reconstructed 3D images and fistulography images was performed in a three-point scale (1 = poor, 2 = average, 3 = good) by both radiologists in consensus.

**Paper II**

**Patient data**

This is a retrospective study comparing two groups of patients. One group included patients operated with a DIEP flap between March 2006 and March 2007 (n = 70 reconstructions in 59 patients). All patients had a preoperative imaging work-up with a CTA of the lower abdomen. The control group consisted of patients operated with a DIEP flap between March 2005 and March 2006 (n = 68 reconstructions in 59 patients). Their preoperative imaging work-up consisted of unidirectional Doppler sonography (performed by the surgeon undertaking the operation) that was standard procedure in our centre prior to CTA introduction.

A detailed analysis of patient and surgical data is seen in table 2.

From the CTA group and the control group patients that received a delayed, unilateral reconstruction were selected and compared in respect to surgery time, complications and flap failure. The selection was performed in order to compare as similar surgical procedures as possible.
### Table 2.
Patient data.

<table>
<thead>
<tr>
<th></th>
<th>CTA group (n = 70 reconstructions)</th>
<th>Control group (n = 68 reconstructions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean age</td>
<td>49.7 years (SD ± 9.3)</td>
<td>49.9 years (SD ± 7.0)</td>
</tr>
<tr>
<td>Mean ASA classification</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Preoperative radiotherapy</td>
<td>44.3%</td>
<td>63.2%</td>
</tr>
<tr>
<td>Mastectomy indication</td>
<td>Breast cancer (26% primary 74% delayed)</td>
<td>- Breast cancer 94.1% (20% primary. 80% delayed)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Poland’s syndrome 3%</td>
</tr>
<tr>
<td>Mastectomy indication</td>
<td></td>
<td>- Deformities after the removal of infected prosthesis 3%</td>
</tr>
<tr>
<td>Unilateral reconstruction</td>
<td>48 patients (68.5%)</td>
<td>50 patients (84.7%)</td>
</tr>
<tr>
<td>Bilateral reconstruction</td>
<td>11 patients (31.5%)</td>
<td>9 patients (15.3%)</td>
</tr>
<tr>
<td>Receptor vessel</td>
<td>Internal mammary a. 87%</td>
<td>Internal mammary a. 74%</td>
</tr>
<tr>
<td></td>
<td>Circumflex scapular a. and thoracodorsal vessels 13%</td>
<td>Circumflex scapular vessels 26%</td>
</tr>
<tr>
<td>Anastomosis type</td>
<td>End to end 81%</td>
<td>End to end 100%</td>
</tr>
<tr>
<td>Anastomotic material used</td>
<td>Sutures 47%</td>
<td>Sutures 50%</td>
</tr>
<tr>
<td></td>
<td>Clips 47%</td>
<td>Clips 30%</td>
</tr>
<tr>
<td></td>
<td>Rings 6%</td>
<td>Rings 20%</td>
</tr>
<tr>
<td>Superficial vein anastomosis</td>
<td>Cephalic vein 31%</td>
<td>Cephalic vein 60%</td>
</tr>
<tr>
<td></td>
<td>End to end 98%</td>
<td>End to end 100%</td>
</tr>
<tr>
<td>Mean ischemia time</td>
<td>60.6 min (SD ± 25)</td>
<td>61.9 (SD ± 26)</td>
</tr>
</tbody>
</table>

### CTA Imaging
CT examinations were performed in a Siemens Somatom Sensation 16 scanner. Patients were examined supine with arms along their sides. An 18- or 20- gauge intravenous catheter was placed in an antecubital vein of one arm. An injection of 80 mL of low-osmolar, non-ionic, iodinated contrast medium was administered through a power injector with an injection rate of 4 mL/s, chased by 40 mL of saline bolus. Bolus tracking was performed with the ROI on the aorta at the level of the aortic bifurcation. Scanning was initiated approximately 10 sec after the ROI reached 100 HU and imaging was performed in a caudo-cranial direction from the femoral head to approximately five cm cranially of the umbilicus.

Images were acquired during a single arterial phase and reconstructed to 1 mm slice thickness with an increment of 0.6 mm.
**Image post-processing**

Axial images were post processed and reformatted into MPR and VRT images in commercially available software. Using the 3D programme the screen was quartered and with a coordinate system and a MPR cursor, pixels could be identified simultaneously in axial, sagittal and coronal planes. In a VRT coronal image of the scanned volume a grid was superimposed with the umbilicus as zero point (Figure 12). Perforators were sought out and analysed in respect to course, intramuscular component, subfascial or epifascial component, branching and calibre. Up to three of the best perforators on each side were identified and marked in the grid coordinate system (Figures 13 and 14). The process was performed bilaterally in all patients by two radiologists in consensus and the findings were discussed preoperatively with the surgeons. A consensus

![Image of post-processing](image)

**Figure 12.**

Coordinate system with MPR cursor in the same pixel in all three planes. VRT image of the skin surface of the lower abdomen with superimposed grid is seen on the lower right side.
agreement was reached regarding which perforators were most suitable. The relevant imaging material was stored in the PACS and the selected perforators were also marked in a schematic grid system on paper, and given to the surgeons (Figure 15). All operating rooms are equipped with computers accessing the PACS archive and giant monitors, so the relevant images could be brought up at any point during surgery.

Figure 13.
Yellow arrows depicting the location of the best perforators on each side.
Figure 14.
VRT image of the skin surface of the lower abdomen with superimposed grid and yellow arrowheads depicting the location of the best perforators on each side.

Figure 15.
Protocol and printed grid system on paper, filled and handed to the surgeons.
**Surgical procedure**
The surgical team consisted of two surgeons and two nurses. One of the two senior surgeons of the section of microsurgery was always present. One surgeon started with flap dissection whereas the other prepared the receptor site. Once both flap and receptor site were dissected and the dominant perforator/s chosen, all other perforators were clamped and a pause of 15 min was made, in order to see if the chosen vessel/s could supply the entire flap. If flap perfusion continued to be satisfactory, the flap was lifted and the vessels anastomosed to the receptor site. After re-establishment of blood flow, the anastomosed flap was formed like the contralateral breast and the donor site closed and sutured.

**Definitions**
Surgery time is defined as the time between the first incision and wound closure.

A complication was classified as any of the following: haematoma, infection, superficial necrosis, seroma, anastomotic failure or a complication of these.

Surgical outcome was rated as: success, partial necrosis (> 10% tissue loss) or failure.

**Statistics**
Data is represented as ± standard deviation (SD). The student t-test and chi-square tests were used for group comparison. Significance was set at p < 0.05. The Statistical Package for the Social Sciences (SPSS 13.0, SPSS Benelux bv, Gorinchem, The Netherlands) was used for statistical analysis.
**Paper III and Paper IV**

Patient data and the imaging part are common for Paper III and IV.

**Patient data**

Thirty-one consecutive patients examined between March 2008 and May 2010 were included in the study. Inclusion criteria comprised patients with complicated renal calculi scheduled to undergo PNL, and referred to our department for a preoperative DECTU examination and planning. Renal calculi were defined as complicated either according to the guidelines of the European Association of Urology or as calculi deemed unable to be eliminated without a PNL procedure. Of the 31 patients two had anatomical abnormalities of the urinary tract: a horseshoe kidney and a duplicated collecting system. In one patient both kidneys presented with complicated calculi and thus were both included. Three patients had undergone a previous PNL procedure on the symptomatic side, four had undergone a retrograde laser lithotripsy, and two were previously operated with pyeloplasty.

The study was retrospective and approved by the Institutional Ethics Committee. Permission was given to review and analyse the DECTU examinations, with waiver of informed consent.

**CTU Imaging**

The CT examination (DECTU with non-enhanced and excretory phase) was performed on a 64-channel dual source scanner (Somatom Definition, Siemens Healthcare). Patient position was prone, with arms extended above the head and a bulky pillow under the abdomen, so as to simulate the operative patient position of the PNL procedure as closely as possible. A non-enhanced study was performed in expirational breath hold and the scan covered the upper abdomen including both kidneys. The dual energy mode was used with tube potential of 140 kV in tube A and a quality reference tube current of 40 mAs. Tube B potential was set at 80 kV, resulting automatically in a quality reference tube current of 220 mAs. Images were reconstructed to 1 mm slice thickness with a 0.7 mm increment using a D30 convolution kernel. A separate dataset for each tube kV was calculated. Furthermore, linearly weighted-average images (based on attenuation information from both detectors and similar to a 120 kV scan) were automatically calculated with a slice thickness of 1 mm and a reconstruction increment of 0.7 mm, using a soft tissue kernel (B31).
Via an 18-gauge cannula placed in a forearm vein, 30 mL of iodinated contrast medium was administered at a rate of 2 mL/s, followed by 50 mL saline bolus administered at the same injection rate, through a power injector.

During the subsequent excretory study, the scan range covered the same area as before after a delay of approximately 450 sec. Image acquisition was performed with tube potential of 140 kV in tube A and 80 kV in tube B. The quality reference tube current for tube A was set at 80 mAs, resulting automatically in a value of 440 mAs on tube B. The images were reconstructed with the same parameters as in the non-enhanced phase. A separate dataset for each tube kV was calculated including also the linearly weighted-average images similar to a 120 kV scan.

Automatic tube current modulation (CARE Dose 4D) was used for both scans.

**Paper III**

**Image reconstruction process**

Images were post-processed in an independent multimodality workplace equipped with commercially available imaging software.

The 80 and 140 kV datasets of the excretory phase were uploaded in the Dual Energy programme and the application Liver Virtual-Non-Contrast (Liver VNC) was selected. The programme can totally subtract iodine from the images (Figure 16), resulting in a series of VNI that was saved in the computer.

The next step in the reconstruction procedure was to create VRT images in the InSpace programme.

The linearly weighted-average images (120 kV) scan of the excretory phase, and the VNI series were loaded in the InSpace programme. The application assigns letter codes to the two series, A and B and they can be manipulated separately. “A” refers to the linearly weighted-average images (120 kV), and “B” to the VNI series. In series A, the primary concern was to keep contrast visible but as transparent as possible (Figure 17a). In series B the primary concern was to make calculi as opaque as possible. Different colour codes were assigned to contrast and to calculi voxels (Figure 17b). The programme offered then the possibility to merge series A and B, resulting in images with the calculi visible within the contrast (Figure 17c).
Figure 16.
By using the application “Fusion Definition MPR” and “Mixing Ratio”, the iodine can be totally subtracted from the images leaving the calculi visible.

Figure 17a.
The linearly weighted-average images (120 kV) scan of the excretory phase and the VNI series were loaded together in the InSpace programme. In series A the primary concern is keeping contrast as transparent as possible so the opacity of the contrast material was kept low.
Figure 17b.
In series B calculi should remain as visible as possible, therefore the opacity of the calculi was kept high.

Figure 17c.
When choosing the merging method “Addition (A+B)” series A and B are merged, rendering calculi visible within the contrast.
In order to choose the optimal tract into the kidney during the PNL procedure, the VRT images were evaluated in the MPR view mode together with MPR images (Figure 18). This enabled the radiologist to assess the kidney and the position of the calculi in a three-dimensional way.

The next step in the reconstruction procedure was to compare VNI and TNI for possible calculi size and form changes. VRT reconstructions of the VNI series were performed and the non-enhanced linearly weighted-average images (120 kV) were also reconstructed in VRT. The parallel viewing mode was then used for the comparison (Figure 19).

The last step was to compare the new technique to the pre-existing image reconstruction technique. The new technique has been described in detail. The decision-based part of the pre-existing image reconstruction technique consisted of parallel viewing of VRT reconstructions of the non-enhanced and excretory phase 120 kV images (Figure 20).

Figure 18.
Choosing the MPR view mode will enable the radiologist to assess calculi, collecting system and adjacent structures in a 3D way, prior to the decision of optimal tract.
Figure 19.
Comparison of TNI (left) and VNI (right) for potential changes in calculi size and form. VRT reconstructions and parallel viewing mode.

Figure 20.
The pre-existing reconstruction technique for choice of optimal tract consisted of VRT images of the non-enhanced (left) and excretory phase series (right), seen in parallel viewing.
Parameters evaluated
A standard protocol was formed and used to evaluate the reconstructed images of each DECTU examination. Parameters measured and evaluated can be seen in detail in table 3.

Table 3.

<table>
<thead>
<tr>
<th>Parameters evaluated</th>
<th>Yes/No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction of VNI in the Dual Energy programme.</td>
<td></td>
</tr>
<tr>
<td>Is it possible?</td>
<td>Yes/No</td>
</tr>
<tr>
<td>Merging of VNI and excretory phase 120 kV images in the InSpace programme and VRT reconstructions:</td>
<td></td>
</tr>
<tr>
<td>Is material characterisation good enough to separate contrast from calculi?</td>
<td>Yes/No</td>
</tr>
<tr>
<td>VRT reconstructions of VNI and TNI and parallel viewing:</td>
<td></td>
</tr>
<tr>
<td>Calculi size change graded in a three-grade scale:</td>
<td>0 Insignificant 1 Average 2 Significant</td>
</tr>
<tr>
<td>Calculi form change graded in a three-grade scale:</td>
<td>0 Insignificant 1 Average 2 Significant</td>
</tr>
<tr>
<td>Comparison of the new and pre-existing image reconstruction technique:</td>
<td></td>
</tr>
<tr>
<td>Is there a change of calculi size and shape in such a degree that the optimal tract choice would have to be modified?</td>
<td>Yes/No</td>
</tr>
<tr>
<td>Presence of drainage tubes (nephrostomies, J-stent) recorded:</td>
<td></td>
</tr>
<tr>
<td>Did they obstruct image reconstruction or evaluation?</td>
<td>Yes/No</td>
</tr>
</tbody>
</table>

The size changes in the three-grade scale were defined as following:

- Insignificant: no visual change and no change of maximum calculi diameter.
- Moderate: moderate visual change and reduction between 2 and 4 mm of maximum calculi diameter.
- Significant: pronounced visual change and reduction of more than 4 mm of maximum calculi diameter/disappearance.
The form changes in the three-grade were defined as following:

- Insignificant: no visual change of calculi.
- Moderate: visual change where overall form is maintained but surface details are erased.
- Significant: pronounced visual change/disappearance.

**Estimation of radiation dose**

For estimation of the radiation doses the effective dose \( (E) \) per examination was calculated from the product of the dose-length product (DLP) and a conversion coefficient \( (k) \) for the upper abdomen as the examined anatomical region \( (E=\text{DLP} \times k) \). The conversion coefficient \( (k = 0.017 \text{ mSv/ (mGy x cm)}) \) was averaged between male and female models from Monte Carlo simulations \(^{53,54}\). The DLP was recorded from the patient protocols of the DECTU examinations for each patient.

**Statistical analysis**

Results are expressed as absolute numbers and as mean ± SD for quantitative variables.

**Paper IV**

**Image reconstruction process**

Images were post-processed in an independent multimodality workplace equipped with commercially available imaging software.

VNI images were created in the Dual Energy programme from the 80 and 140 kV datasets of the excretory phase of each examination.

The number of calculi per renal unit was measured in the TNI (defined as the linearly weighted-average images (120 kV) scans of the non-enhanced phase). Each calculus was assigned a letter code (A, B, C and so forth). The procedure was then repeated for the VNI series. Should calculi disappear, move or alter appearance between the two series, a specific note was made.

For a better comparison between VNI and TNI series and to illustrate possible discrepancies regarding calculi number and appearance, both series were loaded in the InSpace programme of the software and VRT images were reconstructed, which were then viewed simultaneously with parallel imaging (Figure 21).

The following step was the characterization of calculi composition. The 80 and 140 kV scan of the non-enhanced phase of each examination were loaded in the Dual Energy programme. The programme, using informa-
tion from both tubes, automatically identified renal calculi and assigned colouring depending on the chief component (Figure 22). Voxels that demonstrate dual energy properties similar to uric acid are coloured with red, and voxels demonstrating dual energy properties similar to calcium are coloured with blue. Other components such as hydroxypatite and oxalate are so similar to calcium that differentiation is not possible. Figure 23 depicts the diagram used by the software for the automatic colour allocation, and the default parameter settings.

The last step in the reconstruction process was volume, height and attenuation measurements.

The TNI series of each examination was loaded in the “Volume” programme of the software. The applications “interactive” and “freehand ROI” were chosen. The evaluation limits were manually set between 2500 (upper) and 150 (lower) HU. These choices permit the automatic identification of calculus voxels provided that their attenuation lies between the upper and lower limit. The “freehand ROI” enables the evaluator to draw a line around the calculus voxels scrolling slice after slice from top to bottom, until the whole calculus is covered (Figure 24). The programme then calculates the calculus volume, height, and mean HU attenuation, also colouring the calculus voxels with a random colour (Figure 25).

Figure 21.
VRT reconstructions of renal calculi in the InSpace programme and parallel viewing. TNI reconstructions on the left part of the image and VNI on the right. Note the changes, predominantly on calculi size.
Figure 22.
Calculi material characterization process in the dual energy programme. After choosing the “kidney stone” application, calcium containing structures are coloured with blue (default parameters of the vendor).

Figure 23.
Image of the diagram used by the software for the automatic colour allocation of different materials, and the default parameter settings.
Figure 24.
Image reconstructions in the volume programme. The TNI series of one examination is loaded in the volume programme. Then a line is manually drawn around the perimeter of the calculus slice by slice. Observe the thin pink line surrounding the white calculus.

Figure 25.
After terminating the manual evaluation, the programme colours what it perceives as calculi voxels with a random colour, and presents the results in table form.
This procedure was manually repeated separately for all calculi in all renal units first in the TNI, then in the VNI series. Calculi measuring ≤ 3 mm in maximum diameter (defined as the longest diameter from edge to edge) were excluded from volume measurements.

**Parameters evaluated**

A standard protocol was formed and used to evaluate the reconstruction steps and images of each DECTU examination. Parameters measured and evaluated can be seen in detail in table 4.

Two radiologists in consensus performed the image reconstruction and evaluation process; A.M. had a 20-year experience in image reconstructions and PNL procedures and A.D. had a five-year experience in image reconstructions and abdominal radiology.

<table>
<thead>
<tr>
<th>Table 4.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameters evaluated</strong></td>
</tr>
<tr>
<td>Construction of VNI in the Dual Energy programme. Is it possible?</td>
</tr>
<tr>
<td>Number of calculi measured in True Non-enhanced Images (TNI)</td>
</tr>
<tr>
<td>Number of calculi measured in Virtually Non-enhanced Images (VNI)</td>
</tr>
<tr>
<td>Calculi ≤ 3 mm not visible in VNI</td>
</tr>
<tr>
<td>Material characterization for each calculus Uric acid component?</td>
</tr>
<tr>
<td>Calculi in VNI and TNI analysed in the Volume programme regarding: Volume, Height, Attenuation in HU</td>
</tr>
</tbody>
</table>
Statistical analysis
Results are expressed in absolute numbers and, if distributed normally, in means.

Bland-Altman’s method of differences was used to evaluate the agreement between the VNI and TNI estimation of volume and height. Since TNI is considered the reference method, it was the differences between the two methods that were plotted against TNI instead of the averages\textsuperscript{55}. To assess if there was a proportional bias with increasing size of volume or height a marginal regression model was fit to the data from the Bland-Altman analysis. The marginal model was estimated by generalized estimating equations (GEE) using an exchangeable correlation structure to control the dependence between calculi within the same patient. Due to the small number of large calculi two sensitivity analysis were performed, one for volume based on calculi with TNI estimated volume $< 2 \text{ cm}^3$ and one for height based on calculi with TNI estimated height $< 4 \text{ cm}$.

A calibration model for attenuation was estimated using inverse regression. The difference between the predicted and the observed attenuation was calculated and plotted against the observed value.

A p value of $< 0.05$ was considered statistically significant. All statistical analyses were performed using SAS version 9.3 software (SAS Institute Inc., Carey, NC, USA).
Results

Paper I

During the study period a total of 31 patients were examined with CTA. Following CTA, 24 patients underwent fistulographies, the mean time between CTA and fistulography being 26 ± 17 days (range 0 - 65 days). The CTA examination times varied between 10 - 15 min. Post processing and image reconstruction took approximately 20 min. Fistulography examination times varied between 30 - 90 min. No adverse contrast reactions were seen.

CTA image interpretation

Comprehension of the anatomy of the AVF/AVG and the whole vascular tree to the heart was graded in a three-point scale and results are shown in table 5. A total of 92 segments were analysed and 75% scored good.

Table 5.

Comprehension of the vascular anatomy in the analysed segments. There are only 30 segments in the forearm column since one patient had an upper arm AVF.

<table>
<thead>
<tr>
<th></th>
<th>Forearm n = 30</th>
<th>Upper arm n = 31</th>
<th>Central n = 31</th>
<th>Total n = 92</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor</td>
<td>3 (10%)</td>
<td>1 (3%)</td>
<td>2 (6.5%)</td>
<td>6 (6.5%)</td>
</tr>
<tr>
<td>Average</td>
<td>4 (13%)</td>
<td>4 (13%)</td>
<td>9 (29%)</td>
<td>17 (18.5%)</td>
</tr>
<tr>
<td>Good</td>
<td>23 (77%)</td>
<td>26 (84%)</td>
<td>20 (64.5%)</td>
<td>69 (75%)</td>
</tr>
</tbody>
</table>

Table 6 gives details on the grading of the quality of contrast enhancement in all segments. An 83.5% scored good. Four patients had artefacts of varying intensity in the upper arm and in the central vessels and these were due either to pacemaker cables or to dental filling material (Figure 26). VRT images were more sensitive to artefacts than MIP images.

In ten patients the veins of the central segments were difficult to assess due to inadequate contrast enhancement. One of these patients had an AVF occlusion and the remaining nine had a significant AVF/AVG stenosis. Another phenomenon observed in three patients, was the isolated compression of the axillary vein at the level of the thoracic inlet, which was interpreted as a pseudostenosis.
Table 6.
Quality of contrast enhancement of AVF/AVG and the remaining vascular tree in CTA reconstructed images in 31 patients (92 segments).

<table>
<thead>
<tr>
<th></th>
<th>Forearm n = 30</th>
<th>Upper arm n = 31</th>
<th>Central n = 31</th>
<th>Total n = 92</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor</td>
<td>0</td>
<td>0</td>
<td>5 (16%)</td>
<td>5 (5%)</td>
</tr>
<tr>
<td>Average</td>
<td>1 (3%)</td>
<td>4 (13%)</td>
<td>5 (16%)</td>
<td>10 (11%)</td>
</tr>
<tr>
<td>Good</td>
<td>29 (97%)</td>
<td>27 (87%)</td>
<td>21 (68%)</td>
<td>77 (83.5%)</td>
</tr>
</tbody>
</table>

Figure 26.
VRT image of upper arm and central segments. Artefacts from dental filling material are clearly seen.
**Fistulography group**

In the 24 patients that subsequently underwent fistulography, CTA had demonstrated a total of 37 significant stenoses. They were located as following: body of AVF/A VG 48.6% (Figure 27), AVF/A VG arterial anastomosis 32.4% (Figure 27), AVG-venous anastomosis 16% (Figure 28),

**Figure 27.**
VRT image depicting stenoses at the body of an AVF (unfilled arrow) and near the arteriovenous anastomosis (filled arrow).
Figure 28.
Stenoses at an AVG-venous anastomosis at the level of the elbow. The area in VRT reconstructions (a and b), during fistulography (c and d) and after PTA (e). The filled arrows indicate the stenosis at the AVG-venous anastomosis and the unfilled arrows the stenosis in the efferent vein. Notice the pseudoaneurysm in between.
and upper arm vein 3%. Fistulography could verify all 37 stenoses but demonstrated two more. Of these, one was located in an AVG-venous anastomosis and the other in the central venous vessels. These two false negatives reduced the sensitivity of CTA to 95%.

In the subjective three-point CTA-fistulography correlation scale, 88% scored good, 8% scored average and 4% scored poor. All 24 patients were treated with PTA and balloon angioplasty with good technical results. No stents were placed.

**Non-fistulography group**

Seven of the 31 patients examined with CTA were not followed up with fistulography within the study time limits. There were various reasons supporting these decisions: one patient had a total AVF occlusion and received a CVC the same day (Figure 29). One patient had declining haemodialysis blood flows and a proven AVF stenosis in the CTA but refused fistulography and the prospect of PTA. One patient had an engorged AVF in the forearm and haemodialysis blood flows of 2.4 L/min with substantial steal. The CTA examination confirmed the clinical suspicion of a highly developed collateral venous network and the reconstructed images guided the surgeons during the subsequent surgical revision. One patient had developed two quick growing aneurysms in his AVF, and ultrasound examination raised the suspicion of stenosis. However, CTA did not confirm the existence of a stenosis, and there were no clinical symptoms of fistula failure. Finally, three patients were referred because of declining access blood flows but the CTA did not reveal any significant pathology. Since the clinical symptoms of dysfunction did not deteriorate (and in one case flows returned to normal) no fistulography follow-up was performed.
Figure 29.
An AVF occlusion, with (a) showing the AVF patent (filled arrow) and the graft patch used at surgery to elongate it (unfilled arrow), is hardly noticeable. The AVF occluded (b), and only the graft patch is now visible.
Paper II

Patient data
During the study period a total of 138 DIEP reconstructions were performed in 118 patients. There were 59 patients in each group. A detailed analysis of patient and surgical data was seen on table 2. No adverse contrast reactions occurred.

Surgery time
The mean surgery time in the CTA group was shown to be significantly lower than in the control group with p < 0.001. When the subgroup of patients receiving delayed unilateral reconstruction was compared in the two groups, difference in surgery time was also shown to be significantly lower in the CTA group with p < 0.001. Details can be seen in table 7.

Table 7.
Differences in surgery time.

<table>
<thead>
<tr>
<th></th>
<th>CTA group (n = 70)</th>
<th>Control group (n = 68)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean surgery time</td>
<td>313 min (SD ± 107)</td>
<td>395 min (SD ± 109)</td>
</tr>
<tr>
<td>Mean surgery time in patients with unilateral delayed reconstruction</td>
<td>n = 41</td>
<td>n = 44</td>
</tr>
<tr>
<td></td>
<td>264 min (SD ± 62)</td>
<td>354 min (SD ± 83)</td>
</tr>
</tbody>
</table>
Complications and flap failure
There were fewer complications in the CTA group (20%) than in the control group (25%). The difference however was not statistically significant. A detailed analysis is presented in table 8. There were no flap failures in the CTA group but one complete flap failure in the control group and partial necrosis in three flaps.

<table>
<thead>
<tr>
<th>Complications</th>
<th>CTA group (n = 70)</th>
<th>Doppler group (n = 68)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infection</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Hematoma</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Superficial necrosis</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Seroma</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Anastomosis revision</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>(arterial/venous occlusion)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complication percentage</td>
<td>20%</td>
<td>25%</td>
</tr>
<tr>
<td>Flap failure</td>
<td>0</td>
<td>Total necrosis: 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Partial necrosis: 3</td>
</tr>
</tbody>
</table>

Paper III
The study included 31 patients; two patients were excluded because of severe artefacts on the DECTU examination, making both image reconstruction and scan evaluation very difficult. Of the remaining 29 patients, one had a horseshoe kidney that for practical reasons was divided in a right and a left half for the evaluation, and one had bilateral complicated calculi so both kidneys were included in the study. The total of renal units (defined as the intrarenal collecting system of a kidney) was therefore 31.

The DECTU examination time was approximately nine minutes. No adverse contrast medium reactions were seen. Image reconstruction and evaluation took approximately 15 min per renal unit. Evaluation was performed by two radiologists in consensus, one with a 20-year experience in image reconstructions and PNL procedures (A.M.), and one with a five-year experience in image reconstructions and abdominal radiology (A.D.).
The construction of VNI in the Dual Energy programme was possible and interpretable for all renal units.

The merging of VNI and excretory phase 120 kV images in the InSpace programme with subsequent VRT reconstructions to achieve calculi visible within contrast was also possible and interpretable for all renal units.

VRT reconstructions of VNI and TNI were performed and compared with parallel viewing regarding calculi size and form change. In the three-grade scale the calculi size change scored a median of 1 (moderate) whereas the calculi form change scored a median of 0 (insignificant). These results can be seen in greater detail on table 9.

<table>
<thead>
<tr>
<th>Grade of change</th>
<th>Calculi size change</th>
<th>Calculi form change</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Insignificant)</td>
<td>41%</td>
<td>62%</td>
</tr>
<tr>
<td>1 (Average)</td>
<td>50%</td>
<td>27%</td>
</tr>
<tr>
<td>2 (Significant)</td>
<td>9%</td>
<td>11%</td>
</tr>
</tbody>
</table>

Comparison of the new and pre-existing image reconstruction technique was performed by the more experienced of the two radiologists (A.M.). The question was if there was a change of calculi size and form in such a degree that choice of optimal tract would have to be modified. The radiologist was blinded to previously taken clinical decisions on the choice of optimal tract. Optimal tract was first decided on the reconstructed images with the new technique. Then the radiology reports of the 29 DECTU examinations were pulled out from the digital archive and the optimal tract choice of that time (performed with the pre-existing reconstruction technique) was reviewed. The revision showed complete agreement between the old and new choice of optimal tract in all renal units.

A drainage catheter was present in seven renal units: a nephrostomy catheter in six and a double J-stent in one. The presence of drainage catheters did not inhibit image reconstruction or evaluation in any case.

The average effective dose for the DECTU examinations was $7.2 \pm 2.4$ mSv (3.7 - 11). The average effective dose for the excretory series of the DECTU examinations was $5.3 \pm 2.2$ mSv (2.5 – 9). The average effective dose for the unenhanced series was $1.9 \pm 0.8$ mSv (1.1 - 4.7) and accounted for 28% of the total effective dose.
Paper IV

A total of 31 patients were included in the study but in two patient examinations severe artefacts emerged, rendering the interpretation of reconstructed images impossible. Thus only 29 patients were evaluated with a total of 31 renal units (defined as the intrarenal collecting system of one kidney): one patient had a horseshoe kidney, which for reasons of practicality was divided in a right and a left half, and one patient had bilateral complicated calculi.

The total DECTU examination time was approximately nine minutes. There were no adverse contrast reactions. Image reconstruction and evaluation was of variable duration, depending on the number of calculi in each renal unit.

The construction of VNI in the Dual Energy programme was possible and interpretable for all renal units.

The number of calculi measured in the TNI series was 122 (mean of 3.9 calculi per renal unit, range 1 - 18). The number of calculi measured in the VNI series was 112 (mean of 3.6 calculi per renal unit, range 1 - 16) resulting in a sensitivity of 92%.

A total of ten calculi visible in the TNI series were not visible in the VNI series. Nine disappeared completely and one merged with a conglomerate of adjoining calculi, due to patient motion. Of the nine calculi that disappeared, one had a maximum diameter of 3.8 mm and the remaining eight were smaller than 3 mm, (mean diameter 1.8 mm, range 0.5 - 3.8). The mean attenuation value of the nine calculi in the TNI series was 442 HU (range 220 - 894). These nine calculi were not included in measurements in the Volume programme.

The dual energy material characterization showed that none of the 122 calculi had a uric acid component.

Of the 112 calculi present in both TNI and VNI series, four had a maximum diameter of less than 3 mm and were excluded from measurements in the Volume programme. Furthermore, separate measurements were not feasible for 22 calculi due to the formation of calculi constellations with blurry margins in the VNI series. Consequently, Volume measurements were performed for a total of 86 calculi in each series. In seven calculi the programme calculated volumes of zero, so these calculi were excluded from the statistical calculations.

Statistical calculations were therefore performed for 79 calculi. Data on calculi volume, height and attenuation in mean values for TNI and VNI is shown in detail in table 10.
The degree of agreement between TNI and VNI was evaluated and presented by scatterplots and Bland-Altman plots (Fig 30). For the volume there was a significant (p = 0.007) proportional bias as VNI increasingly underestimated the volume for increasing TNI values. In order to evaluate the impact of a few large calculi the model was re-estimated on calculi with volume < 2 cm³ and there was still a significant proportional bias (n = 69 calculi, slope = 0.18; p < 0.001). Figure 30g is based on between-methods percentage differences and shows that smaller calculi were affected more since they lost a larger percentage of their volumes compared to larger calculi.

The comparison between calculi height in the TNI and VNI series revealed an underestimation by VNI and this discrepancy slightly increased with growing calculi size (slope = 0.04; p = 0.039). Ignoring this slight increase the VNI series underestimated calculi height by a mean of 0.15 cm. The potential effect of one outlier and two large calculi was evaluated by omitting these three observations, and it resulted in a mean difference of 0.17 cm and a significant proportional bias (slope = 0.07; p = 0.039).

Finally, figure 30f shows that the two methods give systematically different attenuation estimates and the comparison between TNI and VNI series resulted in the calibration equation TNI=(VNI-58.2)/0.53. Figure 30f shows that calculi with attenuation > 500 HU have a greater variability of the differences compared to calculi with attenuation < 500 HU.

### Table 10.
Sample sizes of 79 calculi in 31 patients.

<table>
<thead>
<tr>
<th>Volume (cm³)</th>
<th>Height (cm)</th>
<th>Attenuation (HU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNI</td>
<td>VNI</td>
<td>TNI</td>
</tr>
<tr>
<td>Mean</td>
<td>0.96</td>
<td>1.41</td>
</tr>
<tr>
<td>SD</td>
<td>1.50</td>
<td>1.07</td>
</tr>
<tr>
<td>Min</td>
<td>0.02</td>
<td>0.31</td>
</tr>
<tr>
<td>Max</td>
<td>8.82</td>
<td>7.24</td>
</tr>
</tbody>
</table>

The degree of agreement between TNI and VNI was evaluated and presented by scatterplots and Bland-Altman plots (Fig 30). For the volume there was a significant (p = 0.007) proportional bias as VNI increasingly underestimated the volume for increasing TNI values. In order to evaluate the impact of a few large calculi the model was re-estimated on calculi with volume < 2 cm³ and there was still a significant proportional bias (n = 69 calculi, slope = 0.18; p < 0.001). Figure 30g is based on between-methods percentage differences and shows that smaller calculi were affected more since they lost a larger percentage of their volumes compared to larger calculi.

The comparison between calculi height in the TNI and VNI series revealed an underestimation by VNI and this discrepancy slightly increased with growing calculi size (slope = 0.04; p = 0.039). Ignoring this slight increase the VNI series underestimated calculi height by a mean of 0.15 cm. The potential effect of one outlier and two large calculi was evaluated by omitting these three observations, and it resulted in a mean difference of 0.17 cm and a significant proportional bias (slope = 0.07; p = 0.039).

Finally, figure 30f shows that the two methods give systematically different attenuation estimates and the comparison between TNI and VNI series resulted in the calibration equation TNI=(VNI-58.2)/0.53. Figure 30f shows that calculi with attenuation > 500 HU have a greater variability of the differences compared to calculi with attenuation < 500 HU.
Figure 30.
Method comparison between TNI and VNI in respect to volume, height and attenuation of calculi. Sample size of 79 calculi in 31 patients.

a) Calculi volume estimated by VNI and by TNI with the line of equality (dotted line) and the regression line (solid line).

b) Bland–Altman plot comparing the calculi volume estimated by VNI and by TNI. Between-methods differences, TNI – VNI on y-axis and TNI on x-axis. The existence of a proportional bias is shown by the significant slope of the line regressing the difference on TNI (slope = 0.25; p = 0.007). The regression line is shown with 95% individual confidence limits bands.

c) Calculi height estimated by VNI and by TNI with the line of equality (dotted line) and the regression line (solid line).

d) Bland–Altman plot comparing the calculi height estimated by VNI and by TNI. Between-methods differences, TNI – VNI on y-axis and TNI on x-axis. The existence of a proportional bias is shown by the significant slope of the line regressing the difference on TNI (slope = 0.04; p = 0.039). The regression line is shown with 95% individual confidence limits bands.

e) Calculi attenuation estimated by VNI and by TNI with the line of equality (dotted line) and the regression line (solid line).

f) The difference between predicted and observed calculi attenuation on the y-axis and attenuation by TNI on the x-axis. The calibration model obtain by inverse regression $TNI = (VNI - 58.2)/0.53$.

g) Bland–Altman plot comparing the calculi volume estimated by VNI and by TNI. Between-methods percent differences, $100\times(TNI - VNI)/TNI$ on y-axis and TNI on x-axis.

h) Bland–Altman plot comparing the calculi height estimated by VNI and by TNI. Between-methods percent differences, $100\times(TNI - VNI)/TNI$ on y-axis and TNI on x-axis.
Discussion

Paper I

The number of patients in need of chronic haemodialysis due to renal failure is increasing. AVF, particularly the radiocephalic, is the vascular access of choice for haemodialysis and should be closely monitored. Prospective surveillance of both AVF/AVG detects problems at an early stage, and in combination with timely intervention, protects the access from failure. In addition to the surveillance methods available at haemodialysis wards, ultrasound has been a useful diagnostic tool in AVF/AVG dysfunction. However, fistulography with DSA has been the gold standard, offering superior diagnostic and interventional capacity.

With the evolution of CT scanners to multidetector configuration, and the increase of temporal and spatial resolution, CTA became possible. Lin et al. described it for the first time in a vascular access setting in 1998. They examined 9 AVF-patients with both CTA and DSA and found near identical results comparing the two methods. Cavagna et al in their study from 2000, where 13 patients were examined with CTA, MRA and DSA, reported 100% sensitivity and specificity for CTA. Likewise, Ko et al described 98.7% sensitivity and 97.5% specificity, and found the CTA examination of failing AVF and AVG to be an accurate method and a non-invasive alternative to DSA. Similar publications followed.

Magnetic resonance angiography (MRA) has also been used in the imaging of failing AVF and AVG, and the two first reports describing this were published in 1991. In the subsequent studies of Konermann and Laissy no intravenous contrast medium was used, the field of view was limited, and it was difficult to differentiate arteries from veins. MRA was also found to overestimate stenosis. These were some of the early problems the MRA technique grappled with. With time the technique developed and in the study of Froger et al from 2005, results and imaging were impressive. The study used fistulography as the gold standard and reported a sensitivity and specificity of MRA for detection of stenosis, of 97% and 99% respectively. Unfortunately, the recognition of the link between nephrogenic systemic fibrosis (NSF) and gadolinium-containing contrast agents in 2006 subsequently precluded the use of these contrast agents in the imaging of patients with renal failure.

The aim of this study was to illustrate the usefulness and the impact of CTA with 3D image reconstructions in dysfunctional AVF and AVG. Our results confirm CTA as an excellent diagnostic tool and as a valuable step in the work-up of these patients prior to fistulography. The anat-
omy of the AVF/AVG and of the entire vascular tree to the level of the heart was illustrated in a comprehensive manner in 93.5% of the evaluated segments. AVF/AVG pathology and associated vascular pathology was depicted. Based on the CTA the appropriate clinical decisions were made: 24 patients who had obvious stenotic pathology and were in need of fistulography and PTA proceeded to these examinations, the patient who needed surgical revision due to the engorged AVF went directly to surgery, and the patient with an occluded AVF received directly a CVC. The CTA images together with the 3D image reconstructions provided a “road-map” on which the fistulography approach was based. The intervention was thus customised for each patient and decisions concerning venous or arterial access, antegrade or retrograde puncture, number of stenosis to treat, and pathology in efferent or central veins were made. In several cases the fistulographies would not have been successful without the previous CTA imaging.

The correlation between CTA with 3D image reconstructions and the fistulographies was found to be good in 88% of the patients and average in 8%. These results render CTA as a reliable and accurate diagnostic method in dysfunctional AVF and AVG and are in accordance with previously described findings.

There are however several concerns and limitations in this study.

Regarding the two false-negative findings, retrospective re-evaluation of the CTA images could still not identify them. The quality of contrast enhancement was poor in 5.5% of the analysed segments, all located centrally. The phenomenon was more prominent when a severe AVF/AVG stenosis was present. Other studies do not mention findings of inadequate opacification of the central vessels, but do mention the occurrence of pseudostenosis linking it with patient positioning during examination.

The study design was not favourable for an objective comparison of CTA and fistulography. When CTA was being established as a new method in the haemodialysis patient population of our centre, the early results were so positive, that a study design involving both CTA and fistulography in the entire study population was deemed unethical. Also, potential bias may have occurred when the CTA images were analysed prior to fistulography and the procedure design was based on them. An approach where the radiologist performing the fistulography would be blinded to the CTA results would have been more objective. In the four cases in which CTA did not show any convincing pathology, the nephrologists in consensus with the radiologists elected to wait and not proceed
to fistulography. During the remaining study time, none of these patients returned to the Radiology Department with renewal of symptoms indicating AVF/AVG failure. This supports the CTA findings.

Another aspect is the use of iodinated contrast medium in patients who might have a small percentage of residual renal function. The referring nephrologists did not raise that concern for any of the patients in the study population. It is however imperative to be aware of the fact that haemodialysis patients might have a residual renal function and be vigilant before using iodinated contrast medium intravenously.

An additional concern is the radiation issue. Radiation dose to the patients during CTA or fistulography was not included in the analysed parameters, so no comparison can be made. Nevertheless, it is indisputable that patients received a higher cumulative dose to the head during CTA than during fistulography alone. We have observed however that since the introduction of CTA in this patient population, the number of fistulographies and the length of the procedures have decreased. Based on the above findings, CTA has now become an accepted and well-established procedure in our centre.

**Paper II**

When Koshima et al published their study regarding the “paraumbilical perforator-based flap” in 1992, they based it on the observation that most perforators from the inferior epigastric artery were found in the periumbilical area. Allen and Treece described “the feasibility of transfer of fat and skin from the lower abdomen without muscle sacrifice” in 1994. A total of 15 breast reconstructions were performed with DIEP flaps supplied with up to three perforators with 100% flap survival. Their conclusion was that the DIEP technique had all the advantages of the free TRAM flap, with decreased probability of ventral hernia or muscle weakness of the abdominal wall. For a little more than a decade, the DIEP and SIEA flap gained ground compared to the free TRAM flap. In 2006 the articles of Alonso-Burgos et al and Masia et al were published in the same issue of the Journal of Plastic, Reconstructive and Aesthetic Surgery. They were the first publications to describe CTA of the lower abdomen as a useful tool for preoperative planning of breast reconstructions with DIEP and SIEA flaps. The study of Alonso-Burgos et al included six patients examined with a four-detector-row CT scanner and 3D image reconstructions were performed. The superimposed grid and coordinate system with the umbilicus as zero point was described for the first time. In addition, a 100% correlation between perforators identi-
fied in the CTA images and operative findings was reported. Masia et al presented a retrospective study of 66 cases examined with a 16 detector-row CT scanner, with image reconstruction and identification of the best perforators in consensus with the senior plastic surgeon performing the operations. Of the 66 cases the first 36 were operated with complete flap dissection as a means of validating the CTA findings. When CTA was shown to be accurate, the remaining 30 cases were operated by basing the flap around the pre-chosen perforator. They also reported reduction in surgery time in the latter group with an average of 100 min/procedure and a 100% positive predictive value of CTA for the entire group.

CTA in the preoperative breast reconstruction setting was introduced to our centre after a joint radiological-surgical visit to the centre of the Masia group. Our first patient was examined in March 2006 and the CTA protocol and 3D image reconstruction process were repeatedly modified until results were satisfactory. Breast reconstructions with DIEP/SIEA had been undertaken in our centre since 2000 and during a five-year period a total of 377 perforator flap procedures (371 DIEP and 6 SIEA) were performed. During the two-year period from January 2004 to January 2006 the mean surgery time for unilateral delayed reconstruction varied between five and eight hours (300 and 500 min). This study was undertaken shortly after the introduction of preoperative CTA examination.

The aim of the present study was to demonstrate the advantages of CTA of the lower abdomen in the preoperative work-up of patients planned for breast reconstruction with DIEP flaps, with respect to surgery time and complication rates.

Our study was retrospective comparing two groups of patients, one group examined preoperatively with CTA and a control group, examined preoperatively with handheld Doppler. The number of patients in each group was equal (59 patients) but not the number of operations (70 for the CTA group and 68 for the control group). The main outcome measures, as defined by the study protocol, were compared and there was a statistically significant difference in surgery time between the two groups. There were differences in the complication rate, with fewer complications in the CTA group but statistical significance was not reached. No flap failure was observed in the CTA group and there was one flap failure in the control group. No false positives were observed in the CTA group and there was complete agreement between the CTA and surgical findings. Thus, we could report a positive predictive value of 100% for CTA, which is in agreement with other publications. From 2006 onwards CTA replaced Doppler ultrasound as the assessment of choice in the preoperative setting in our centre.
There are several limitations to this study, design being perhaps the most important. A prospective, randomized study would have been the most favourable scientific method to examine the hypothesis but it was clinically and practically not possible. The introduction of CTA in the preoperative work-up of these patients had already taken place and this was strongly supported by the published literature. It was thus argued that it would be unethical to exclude patients from the best possible care including preoperative work-up. The groups were therefore compared in retrospect, and care was taken to make them as similar as possible. It is worth noting that operations in the control group could have been performed up to two years earlier than operations in the CTA group. However it would seem unlikely that learning curve played a significant part in the observed differences, given that the same group of plastic surgeons had already performed more than 370 DIEP flap procedures by the time of the introduction of CTA in March 2006.

This study did not include any documentation or analysis of the preoperative work-up with the handheld Doppler in the control group or its results. Such a comparison would doubtless be of interest. However there have been a series of publications indicating that the sensitivity of handheld unidirectional Doppler is undermined by high false positive and low specificity\(^7,32,34,40\). Colour Doppler is much more accurate and can follow perforators to larger vessels, but in the study of Rozen et al\(^66\) where both CTA and Colour Doppler were performed in eight consecutive patients, CTA was shown to be superior. In contrast, a recent publication by Cina et al\(^67\) where 45 patients were examined with CTA and Colour Doppler, showed that sonography was more accurate in identifying dominant perforators.

Two of the more serious disadvantages of CTA are radiation exposure and the administration of intravenous contrast medium. Dedicated measurements of effective radiation dose were not included in the study design. The scanned area was kept as limited as possible, and the Siemens CT scanner used featured the CareDose 4D programme which modulates the x-ray tube current in accordance to the volume and mass of every individual patient based on a quality reference mAs value. That ensures the minimum possible radiation exposure while retaining the desired image quality, depending on patient size. We did not observe any increase of signal-to-noise ratio of the abdominal wall as Rozen et al\(^68\) and Philips et al\(^7\) have reported. We therefore did not see the need to disable the CareDose 4D programme. Regarding the use of intravenous contrast, it was departmental policy to measure levels of serum creatinine prior to all CTA examinations so that no patients with renal insufficiency would undergo examination, and thus our study population included no such patients.
Shortly after our study was submitted for publication, Philips et al. published a meticulous description of the CTA technique of the abdominal wall, refining and improving both the CTA procedure and the image reconstruction process. They reported an average radiation dose of 6 mSv per examination, a CTA sensitivity of 96% - 100% and a specificity of 95% - 100%. Several studies on this topic have subsequently been published, including MRA of the abdominal wall and comparative CTA and Duplex studies. Regardless of the preoperative method used, and notwithstanding the fact that we advocate that CTA is the best available tool in the preoperative work-up of free flap breast reconstructions, the increasing evidence-base on this subject is likely to be very beneficial to patients undergoing mastectomy.

**Paper III and IV**

Dual energy CT was theoretically described in the late 1970s and by the mid 1980s there appeared publications regarding material characterization with different X-ray spectra. However, due to technical limitations, the incorporation of a dual energy CT scanner in everyday clinical practice delayed until 2006. Dual source CT requires two X-ray sources running at different tube voltages, emitting photons of different energies. At the current level of technology a single detector cannot simultaneously differentiate between two photon energies therefore, two detectors are needed, one for the photons of each tube. The two tubes and the two detectors are mounted orthogonally and rotate around the patient simultaneously. Material characterization in dual energy CT is based on the principle that the amount of photons absorbed by any given tissue/material will be different at various photon energies. Therefore the attenuation of tissues/materials varies depending on the tube voltage used, and the difference is more obvious for tissues/materials with high atomic numbers (Z). Since the majority of the components of the human body have low atomic numbers (except calcium), and since the contrast material mostly used (iodine) has a high atomic number, the attenuation of Iodine and calcium will be much higher at 80 kV than at 140 kV, and the differentiation between iodine and body tissues can be quite distinct. This fact has led to the opinion that “the most clinically useful application of dual-energy CT can be expected to be the differentiation of iodine which is generally used in CT as a contrast agent.” Early clinical applications of DECT included bone removal, visualisation and removal of calcified plaques in the vascular system, differentiation of urinary tract calculi and virtual removal of iodine from reconstructed images, resulting in VNI. Johnson et al, in their article from 2006, described the construction and technical theory of VNI. This consists of the three-
material decomposition principle, where every tissue is theoretically composed of two main components and of iodine, permitting detailed tissue characterization. Thus can post-processing algorithms identify iodine in every examined voxel. Subsequent publications emphasized the fact that in appropriate cases where VNI could replace TNI, the numbers of scan acquisitions decreased, thereby reducing radiation dose \(^{12,75}\). 

Though urinary calculi were an initial point of interest for DECT, it was mainly through the scope of material decomposition i.e. differentiating calculi components e.g. uric acid and calcium. To our best knowledge, there are no publications concerning the DECT examination and VNI reconstructions of patients with complicated renal calculi prior to invasive procedures such as PNL. This particular procedure is essential in the management of large and complicated upper urinary tract calculi and is a preferable method of treatment compared to open surgery \(^{42}\), since it has the best stone-free rates \(^{44,76}\). It is currently indicated for any calculus that exceeds 20 mm, staghorn calculi, multiple calculi spread throughout a collecting system, and any calculus burden that cannot be eliminated without an invasive procedure. It is now common praxis to perform a CTU preferably with 3D image reconstructions prior to a PNL procedure for the determination of optimal tract \(^{47}\).

More information can be acquired performing the preoperative CTU with the dual energy technique and taking advantage of its properties than compared to single energy acquisitions.

The virtual subtraction of iodine in patients with renal calculi and the detection of calculi in VNI is also a subject that has interested various researchers.

Scheffel et al \(^{75}\) investigated the sensitivity of VNI derived from the nephrographic phase in detecting urinary calculi (74%) and also size changes of virtually reconstructed calculi, observing that 25% of the calculi in their study were not detected in the VNI series. Several publications on the same subject followed, and a common observation has been that calculi < 3 mm in size are either more difficult to detect, or simply disappear in the VNI series \(^{52,77,78}\).

A common denominator in the majority of the above-mentioned studies is patient population selection. General patient populations have been included, often without established urolithiasis diagnosis, and exhibiting a variety of clinical symptoms (flank pain, haematuria, and suspicion of urinary tract malignancy) that could be attributed to other causes than urinary calculi.
Paper III

The aim of this study was to establish if a new technique of image merging and tissue characterization in patients with complicated renal calculi examined with DECTU prior to PNL, was feasible.

The results of our study indicate that such a new technique is indeed feasible. It was possible to produce VNI from all DECTU examinations and the reconstruction work did not exceed 15 minutes per patient. Merging both VNI and excretory phase images in the InSpace programme produced reconstructions that clearly differentiated between contrast material and calculi. The calculi size and form changes between VNI and TNI were in general not significant, but there was a tendency for VNI images to underestimate calculi size compared to TNI images. The same observations have been made in other studies; Moon et al reported that renal calculi in virtually unenhanced CT images appeared smaller than calculi on unenhanced CT images, attributing the fact to partial subtraction. It can be argued however, that the size change of renal calculi did not significantly influence the choice of optimal tract in our particular group of patients. That was also supported by the comparison of optimal tract choice between the pre-existing and the new reconstruction technique. There were no differences between decisions based on the pre-existing reconstruction technique and decisions based on the reconstructions with the new technique. The choice of optimal tract is a multifaceted procedure where several intra-and extra renal parameters must be taken into account: proximity of adjacent organs, position of ribs, anatomy of the collecting system, calculi burden. It thus requires an overall perspective.

Concerning radiation dose and the estimation of effective dose, several issues should be addressed. The non-enhanced series in our study were all performed with the dual energy mode, since material decomposition of the renal calculi was a separate endpoint. Further information and results on this matter are presented in Paper IV. The effective dose was calculated in the manner described on the materials and methods section of this article, closely following recent publications; in DECT the radiation dose of each tube adds together in a linear manner with each dose independent of the other. Therefore conventional CT dose metrics are fully applicable to dual-source CT. Additionally, it has been shown that estimating effective dose from DLP works as well for single energy as for dual energy examinations.

The dose reduction attained by excluding the non-enhanced series was 1.9 ± 0.8 mSv (1.1 - 4.7), and accounted for 28% of the total effective dose. This percentage is comparable to the 27.6% reduction on total effective dose presented by Moon et al (three-phase acquisition protocol with single energy non-enhanced phase and dual energy nephrographic and excretory phase). Grasser et al reported a total effective dose reduction
of 35.05% by omitting the non-enhanced acquisition in their study of renal masses (three-phase acquisition protocol with single energy non-enhanced phase, dual energy nephrographic phase and single energy low-dose excretory phase). In the next generation of dual energy scanners, radiation doses are expected to be lower due to better tin filters, the larger field of view in detector B and the possibility of using 80 or 100 kV in the low energy tube.

This study has several limitations. It is retrospective in its design. Patient numbers are low (31 patients with complicated renal calculi during a two year period) and it is an undisputed fact that this is a hard selected patient population suffering from an unusual condition that can only be treated in specific, well-trained centres. Clinical decisions on optimal tract had already been taken by the same radiologist (A.M.) who was later involved in the new image reconstruction technique, the comparison of VNI and TNI, and the comparison between optimal tract choice with the new and pre-existing method. That could lead to a recall bias. The dual energy mode was used both in the nonenhanced and excretory series of the 31 DECTU examinations, resulting into higher radiation doses. These CT protocols were however incorporated in a larger study where calculi composition was a separate endpoint.

Our study presents a new reconstruction technique and tissue characterization in patients with complicated renal calculi, facilitating the choice of optimal tract prior to a PNL procedure. We have shown that the TNI series is not an absolute requirement and can be replaced by VNI series. That leads to reduced radiation, which can be of paramount importance to this frequently examined patient group. Further studies are needed to illuminate the importance of reconstructive work and tailor CT protocols in specific patient populations.

**Paper IV**

The aim of this study was to compare VNI and TNI of preoperative DECTU examinations, in patients with complicated renal calculi prior to a PNL procedure. The comparison was done with respect to calculi number, volume, height and attenuation. Our objective was to establish whether previously described findings regarding the virtual reconstruction of small renal calculi, applied for complicated ones.

We chose to use volume analysis as opposed to traditional two-dimensional measurements, believing that volume is a more truthful reflection of the size of a three-dimensional object of variable shape and possessing an uneven surface. Height was included in the automated calculations of the Volume programme and measured the largest distance of a structure
in the cranio-caudal plane. Supplemented by the volume measurements, we believe that these two sizes best reflect the true dimensions of calculi and also render comparison between calculi more accurate. However, an important aspect of the height measurements, is the possibility of calculus movement between examination series: should a calculus change position height measurements will be different. In our material there were 22 cases of calculi migration or formation of calculi conglomerates between examination series; these calculi were excluded from further measurements. Calculi ≤ 3 mm were also excluded from further measurements, based on the various publications that repeatedly report the disappearance of such small calculi when virtually reconstructing images. Furthermore, such small calculi had no clinical significance in our patient population.

The results of our study indicate that the VNI series seem to underestimate calculi in every measured parameter. The number of calculi in the VNI was reduced by ten (8%) compared to the TNI series. The calculi that disappeared were all smaller than 3 mm except one. However, our material included 4 additional calculi smaller than 3 mm in size that remained visible in the VNI series. The attenuation of the disappeared calculi was between 220 and 894 HU, and none had a uric acid component as demonstrated during the material characterization analysis.

The sensitivity for calculus detection in the VNI series reached 92% in our study, a percentage much higher than in the recent study of Mangold et al where sensitivity rates were 53% . Similarly, Takahashi et al in 2010 reported overall sensitivity for calculus detection of 63% in VNI derived from the excretory phase; for calculus measuring 1 - 2 mm in size, sensitivity dropped to 29% . The difference in sensitivity rates may be explained by the difference in patient populations between these studies: our study included patients with known renal calculi of considerable size: a mean height of 1.4 cm and mean volume of 0.96 cm³.

In the comparative volume measurements, calculi in the VNI images were progressively underestimated with increasing size. In general the larger the calculus in TNI the more volume it lost in VNI. The volume loss seemed to originate from the outer perimeter, suggesting that the external surface of the calculus is more susceptible to change by the reconstruction algorithm. However, statistical analysis showed that smaller calculi were affected more since they lost a larger per cent of their volumes compared to larger calculi, resulting to the conclusion that these changes were more marked for smaller calculi (Figure 31). Further there was statistically significant underestimation of calculus height in the VNI series, with a weak tendency for this underestimation to increase with increasing calculi size. Possible explanations for the observed changes in volume and height could include algorithm-related calcium subtraction
Figure 31.
Three cubes with different volumes each are depicted. With the removal of one mm from every dimension for each cube, they lose a part of their volume. The volume loss is largest for the biggest cube, but the percentual loss is largest for the smallest cube. Therefore the smallest cube will be affected the most.

from calculi and noise reduction algorithms that resulted in the loss of small calculi.\textsuperscript{77,78}

The attenuation was likewise underestimated in the VNI series, but independent from calculi size. In the study of Mangold et al, CTU was performed in the new generation DECT with tin-filter technology. VNI were reconstructed and measurements of calculi attenuations in TNI and VNI were performed and showed lower peak values for VNI. The authors attributed this finding to possible partial subtraction or to the characteristics of the stone material itself.\textsuperscript{78} In the recent publication of Sahni et al, attenuation changes between TNI and VNI series were measured for abdominal organs. Attenuation was lower in VNI for aorta and subcutaneous fat but higher for liver parenchyma.\textsuperscript{81} There seems to be no simple explanation for these findings; according to the authors, the
outcome could be influenced by the default settings of the Liver VNC post-processing algorithm. There are pre-assigned attenuation values for specific tissues and in our study these were never manipulated, and the default settings were used.

Our results show that there is a tendency for VNI series to under-estimate calculi number, volume, height and attenuation compared to TNI series.

Our study has several limitations. The study population was small (31 patients with complicated renal calculi) during a two-year period. Several patients had had an invasive procedure on the included renal unit (PNL n = 3 and retrograde laser lithotripsy n = 4), resulting in fragmentation of previously larger calculi and generating a multitude of splinters. Further, 22 calculi had to be excluded from volume measurements due to formation of calculi constellations in the VNI series that were not present in the TNI series. Some cases could be explained with respiration or motion artefacts between the non-enhanced and excretory phase scans of the study, however, in cases with several calculi grouped together in the TNI series it was clear that the reconstruction algorithm could not keep calculi edges apart in the VNI series. We also observed that five calculi yielded larger volumes in the VNI series than in the TNI. A reasonable explanation could be calculi grouping in the VNI series that was still not detected during analysis and comparison.

An additional aspect that should be considered is the accuracy of the linearly weighted-average images that serve as TNI in our study. They are based on 30% attenuation information from the 80 kV scan and 70% attenuation information from the 140 kV scan. They are similar to a 120 kV scan, but still not a true 120 kV scan. Thus it is possible that the image data generated has some degree of error.

The technique of calculi measurements also deserves discussion. At present, there is no international consensus on the best way to measure calculi. They are not elliptical, oval or spherical in shape and therefore the mathematical formulae for calculating such volumes cannot be applied. Instead, the measurements are made by the closest possible approximation.

Our findings indicate that VNI series cannot reconstruct small or large calculi without changes in calculi number, volume, size and attenuation. Further, small calculi are more affected than large ones. VNI series may therefore be a reliable way to detect calculi larger than 3 mm; it is possible that with refinements in technique over time and for selected cases VNI may replace non-enhanced series altogether in patients with complicated renal calculi. The mechanisms of the post-processing algorithms also require further evaluation.
Conclusions

General conclusion
CT with 3D image reconstructions can be useful, crucial and conclusive in the preoperative work-up of selected patient populations scheduled to undergo invasive or operative procedures.

Paper I
CTA with 3D image reconstructions of dysfunctional AVF and AVG in haemodialysis patients, is an accurate and reliable diagnostic tool that helps customize subsequent intervention.

Paper II
CTA of the lower abdomen in the preoperative work-up of patients scheduled for breast reconstruction with DIEP flaps significantly reduces surgery time and seems to result in fewer complications.

Paper III
A new image reconstruction technique and material characterization is feasible in patients with complicated renal calculi examined with a DECTU prior to PNL. Virtual non-enhanced images are sufficient for the preoperative planning, and by omitting the non-enhanced phase radiation dose reduction of 28% can be achieved.

Paper IV
In patients with complicated renal calculi examined with a DECTU prior to PNL, the number, volume, height and attenuation of renal calculi is significantly underestimated in virtual non-enhanced images when compared to true non-enhanced images.
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Sammanfattning på svenska


DT-tekniken har utvecklats snabbt i takt med de tekniska möjheterna. Dagens DT-apparater har nästan inget gemensamt med de från mitten av 70-talet utöver den basala funktionsprincipen. De moderna apparaterna kan undersöka en stor volym med tunna snitt på mycket kort tid och flertalet undersökningar kan genomföras under den tid som patienten orkar hålla andan. Det har också blivit möjligt att utföra tredimensionella (3D) bildrekonstruktioner, som visar en volym från olika vinklar och som kan lyfta fram utvalda vävnader, färgsätta olika vävnader beroende på deras kemiska komposition och förstärka eller skära bort information. 3D bildrekonstruktioner används rutinmässigt i den kliniska vardagen och olika post-processing program möjliggör en snabb hantering.


Syftet med denna avhandling var att visa nytta av DT med 3D-rekonstruktioner i specifika patientpopulationer, inför en operativ eller interventionell åtgärd.
Arbete I
Detta arbete omfattar 31 njurinsufficieranta patienter, som behandlades med hemodialys via en arteriovenös fistel eller graft i armen. Alla patienter hade dåligt fungerande fistlar/graft. De var i behov av en invasiv procedur kallad fistulografi, för att hitta orsaken till den dåliga funktionen och om möjligt korrigera den. Patienterna genomgick en DT-angiografi (DTA) av hela fistel/graft armen före fistulografin. 3D-rekonstruktioner utfördes och i 93,5% av fallen kunde DTA visa kärlanatomin på ett bra och förståeligt sätt. Beträffande diagnos av förträngningar i fistlar/graft uppvisade DTA en sensitivitet på 95% jämfört med fistulografi. 3D-rekonstruktionerna utgjorde en mycket bra karta för planeringen av fistulografin.

Arbete II
Detta arbete handlar om patienter som har genomgått mastektomi (avlägsnande av bröst) och som ska bröstrekonstrueras med en fri lambå (hud och underhudsfett) från främre nedre bukväggen. För att en lambå ska vara viabel måste den blodförsörjas via lämpliga kärl vilka måste följa med lambån. Främre bukväggen nedom naveln försörjs av arteria epigastrica inferior, och dess grenar (perforanter). Tidigare tvingades kirurgen leta blint efter lämpliga perforanter vilket ledde till mycket långa operationstider. Sedan 2006 har vi undersökt dessa patienter med DTA av främre bukväggen och med olika 3D-bildrekonstruktioner kartlagt alla perforanter och tagit fram de mest lämpliga i samråd med kirurgen. Syftet med arbete II var att jämföra en grupp patienter (n = 59) som hade opererats utan preoperativ DTA med en grupp patienter (n = 59) som opererats efter en preoperativ DTA kartläggning. De båda grupperna jämfördes rörande operationstid och komplikationsfrekvens. Det visade sig att i gruppen som hade kartlagts med DTA preoperativt minskade operationstiden signifikant (p < 0,001) och det fanns också en tendens till färre komplikationer.
Arbete III


Arbete IV

Detta arbete utgör en fortsättning på arbete III. Virtuellt nativa bilder av njurstenar jämfördes med äkta nativa bilder hos de 31 patienterna. Njurstenarnas antal, volym, höjd, och attenuering jämfördes. De virtuellt nativa bilderna underskattade antalet njurstenar (sensitivitet 92%), men underskattade även volym och höjd. Konkrementattenueringen på de virtuellt nativa bilderna var generellt lägre än på de äkta nativa bilderna. Mindre konkrement påverkades mer än större och flera konkrement ≤ 3 mm (n = 9) försvann helt.
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