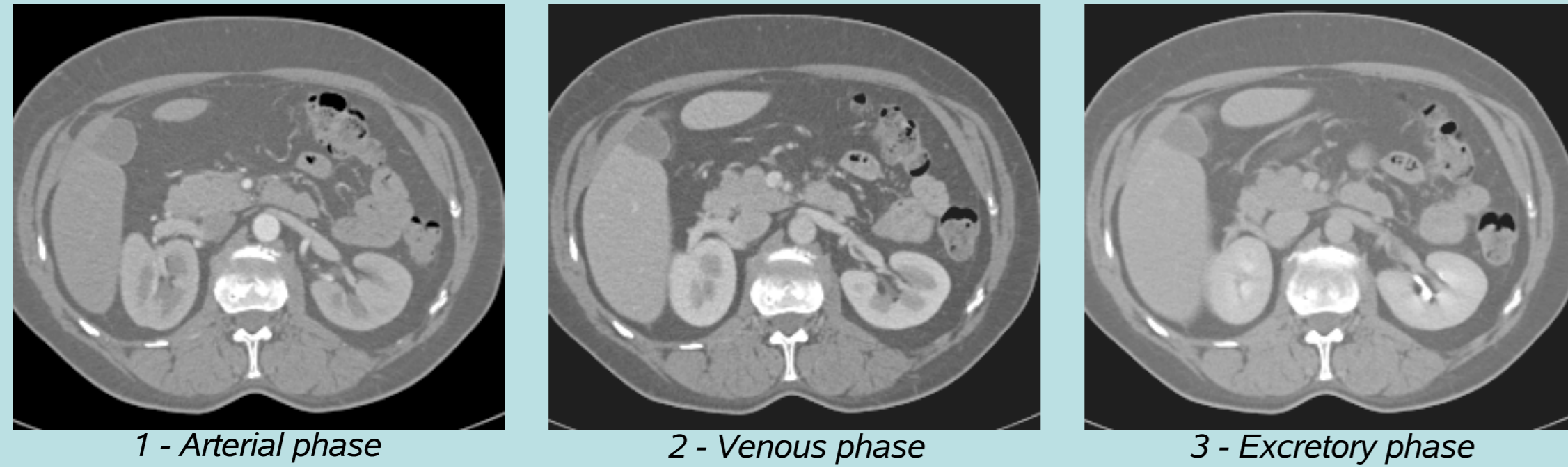


## Clinical Background

In order to plan a surgical operation on the upper urinary tract and anticipate potential difficulties during a laparoscopic intervention, the surgeon must be allowed to study pre-operative images as faithful as possible to the anatomy of the surgical scene, as unveiled to the surgeon during the intervention, and in particular the kidney, the ureter, as well as the surrounding arteries and veins.

Tri-dimensional (3D) vision is therefore required. Current multidetector row CT scan (MDCT) are able to provide high-quality 3D reconstruction, and enable the visualization of even very small blood vessels. However, the different structures have to be clearly distinguished (e.g. arteries vs. veins). To this aim, structures are highlighted in CT images thanks to the intra-venous injection of a iodinated contrast medium.

Three successive CT volumes are acquired to capture the progression of the contrast agent throughout the patient's body, successively highlighting arteries, then veins, then ureters (see below). These structures of interest to the surgeon being originally visible in 3 different CT volumes, the presented work in progress aims at building a single 3D representation of the arteries, veins, kidneys and ureters.



## Material: Images

For each patient, 3 volumes are acquired on a volumetric multidetector row CT scan with 16 channels (Sensation 16, Siemens, Erlangen, Germany), after the intra-venous injection of a contrast product:

- a first volume is acquired about 20 seconds after the injection (arterial phase)
- a second volume is acquired 1 minute later (venous phase)
- a third and last volume is acquired 5 to 10 minutes later (excretory phase)

The delay between two phases does not allow performing all 3 acquisitions within a single breath hold. The same acquisition protocol was followed, aiming at minimizing the patient's motion: careful explanation to the patient and requirement that he/she did not move, each acquisition is made in apnea, synchronized on the same time in the respiratory cycle. Unfortunately, both internal and external motions are unavoidable.

Each of the 3 CT volumes consists of a stack of about 200 to 400 512x512 images (covering the entire kidneys). The axial resolution is approximately 0.6 mm with an inter-slice distance of 0.8 mm for the arterial and venous phases and 1.8 mm for the excretory phase.

## Method, 2nd step: Segmentation

Each volume is processed independently using basic image processing operations within a framework that leverages the physicians' medical knowledge through manual interaction. Operations used are defined below:

- **Min(A,B)**: voxel-wise minimum between volumes A et B
- **Mask(A,M)**: masking, clearing voxels in A which are non null in M (binary volume)
- **Threshold(A,s)**: threshold setting to 1 voxels in A whose value is greater than s, and to 0 all other voxels. The threshold s is chosen manually but varies little (around 1200).
- **CC(M)**: manual operation to select, in a mask volume, connected component of interest (usually less than 10).
- **Surf(M)**: triangulated surface extraction from a mask volume thanks to a marching cube algorithm.

Following the progression of the contrast agent, each structure of interest is extracted from the corresponding original volume: arteries from the arterial phase, veins and renal cortex (kidney) from the venous phase, ureters from the excretory phase. As shown on the right (top line), bones are visible in each acquisition and their segmentation is required in each original volume to clear (mask) highly dense but non-contrasted voxels. The final visualization (see below) makes use of the bone surface extracted from the volume of reference for the affine registration (see below Method, 3rd step: Local affine registration).

On the right is depicted the graph of image processing operations used for the segmentation of veins and kidneys. These structures are the most complicated to extract. A subset only of these operations are used to segment the arteries and the ureters. Under each image, the operation used to generate it is indicated. Arrows tell which images were used as input for each operation.

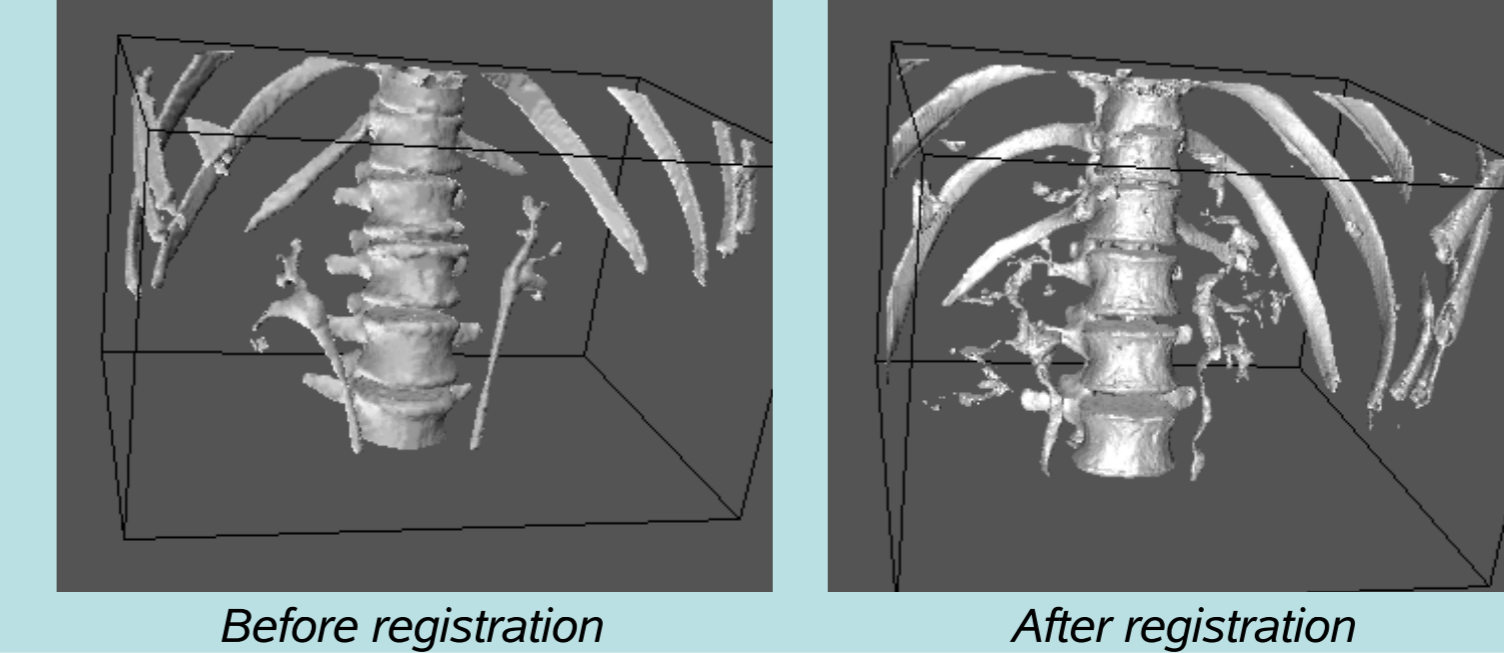
## Technical Background

Preliminary tests showed that structures of interest, such as arteries and ureters, could be extracted through a simple threshold filter (see below, left image, for a threshold-based ureter segmentation). Each structure can be extracted through simple image processing operations, applied on the volume related to the given structure. Even if the voluntary patient's motion can be minimized, internal motion, in particular in the kidney area, still resides. As a result, their superposition and fusion in 3D is not straightforward.

The usual technique consists in, first, a non-rigid registration of each original volume onto a reference volume and, second, a segmentation of each structure in its related registered volume. However, any non-rigid registration method includes a regularization term which tends to extend the motion of large structures (e.g. organs) to neighboring smaller ones (e.g. blood vessels). As a result, the structures of interest, very thin, are highly perturbed in the registration processed (below: the effect of registration on the ureters).

Non-rigid registration followed by segmentation in the warped, registered volume is not adapted here. Indeed, the registration process highly perturbs the very thin structures of interest.

Threshold-based segmentation of the ureters in the excretory phase

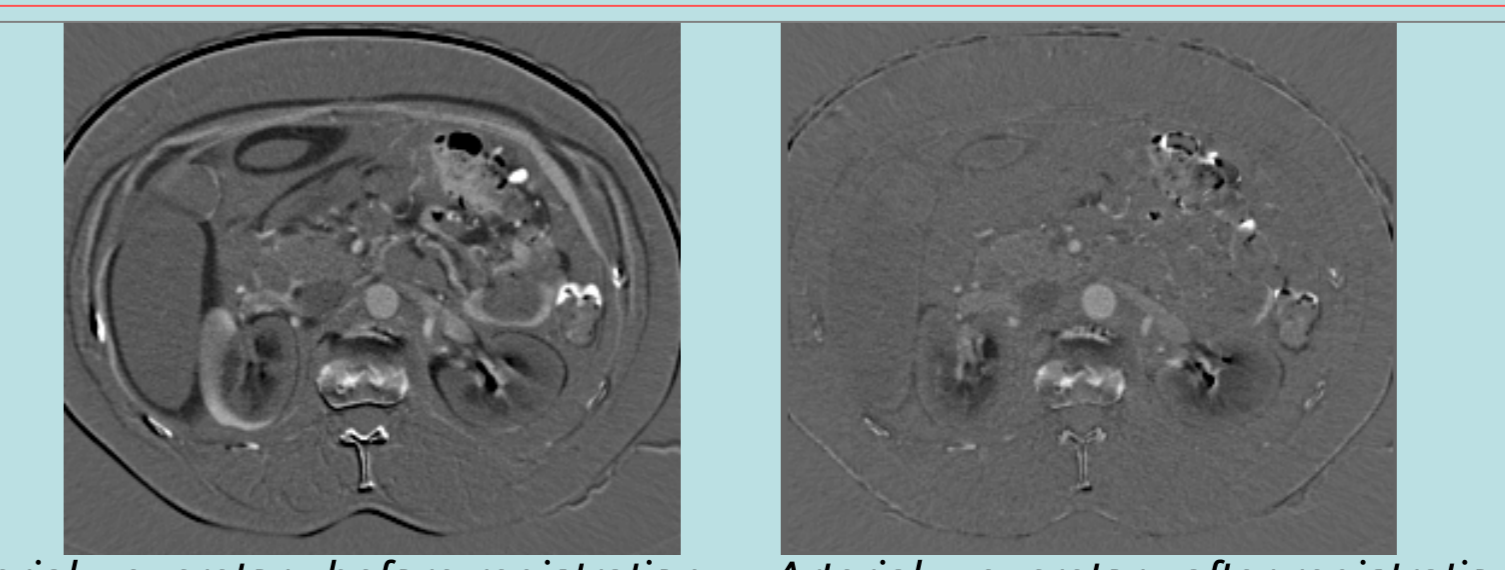


## Method, 1st step: Non-rigid 3D/3D registration

Each volume is resampled so that each voxel is isotropic with voxel size of 1.2 mm (twice the axial resolution). All 3 volumes are then non-rigidly registered by pairs. In the end, each volume appears in its original version, together with 2 registered versions.

Non-rigid registration is performed by optimizing a local 3D cross-correlation score. A hierarchical scheme was followed. A typical result is displayed below with a registration between the arterial and the excretory phases: the voxel-wise difference between both volumes is shown before (left) and after (right) registration. Besides some residual intestinal motion, only the differences due to the contrast agent uptake are preserved.

Hierarchical optimization of the local 3D cross-correlation score enables to non-rigidly register CT volumes by pairs, correcting motion, but preserving contrast agent uptake.



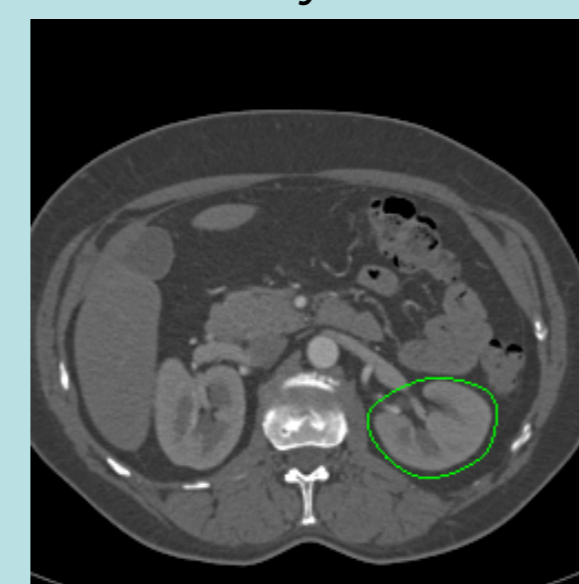
## Method, 3rd step: Local affine registration

Each structure of interest is segmented from its corresponding original volume. As a consequence, they are not registered. One last step will fuse them. The hypothesis is made that the kidney motion is leading the motion of its related structures (arteries, ureter and veins) in its neighborhood. The kidney moves a lot but deforms little. An affine motion is used as motion model for the kidney.

The following local affine registration enables to retrieve the kidney motion:

- gross 3D contouring of the kidney in the venous phase (see figure on the right)
- optimization of the cross-correlation score (Powell algorithm), depending on the parameters of the affine transformation between arterial and venous phases, and then excretory and venous phases
- Affine transformations are applied respectively to the extracted arteries and ureter.

An affine motion is estimated for the kidney, allowing to register the extracted structures so that they match at the kidney level.

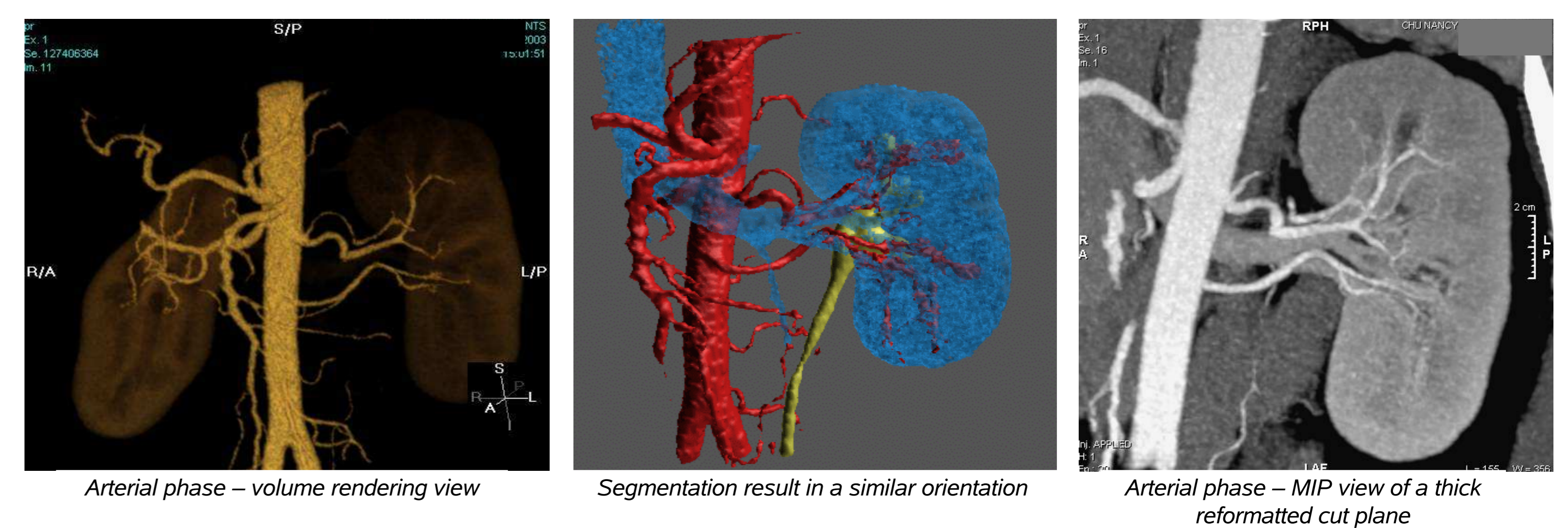
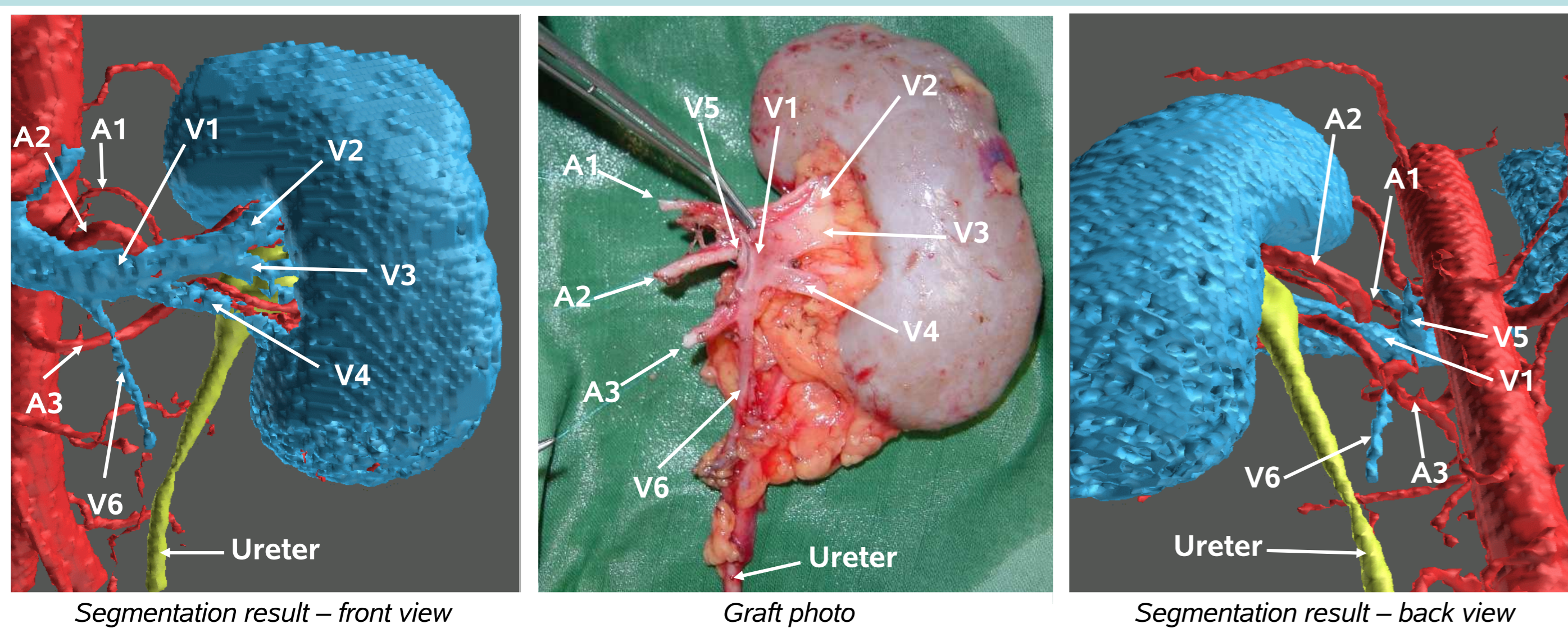


## Results - Validation

To date, 4 patients were processed and analyzed, following this procedure. Each segmented structure was individually colored and a fused volume was visualized and manipulated in 3D in the VRML format.

Experts compared such 3D views to volume rendering (VR) views as well as thick reformatted cut planes of the original volumes (arterial, venous or excretory). 3D views obtained through our procedure were also looked over beside laparoscopic views. Finally, for one case of nephrectomy, our segmentation process was validated with regard to a photo of the extracted graft (see below for examples of comparison).

Comparison to pre-operative (VR views, cut-planes), intra-operative (laparoscopic views) and post-operative (photo of the graft) images showed that the proposed approach has the potential to extract all information relevant to the surgeon.



## Conclusion

A procedure was designed for the segmentation of arteries, veins, ureters, kidneys and bones from 3 contrast-enhanced multidetector row CT acquisitions. This procedure relies on fully automatic non-rigid registration techniques. Besides, it leverages the medical knowledge of surgeons and radiologists through a moderate level of manual interaction and basic image processing operations. A preliminary validation study showed the relevancy of our approach: it provides segmentation results that meet the needs of the surgeon for the planning of a laparoscopic intervention on the upper urinary system.

General critics concerned the lack of visibility of some very small blood vessels (1 to 2 mm in diameter). Future work will aim at correcting such minor errors. The full procedure also calls for an implementation as a graphical user interface.