Virtual simulation, preoperative planning and intraoperative navigation during laparoscopic partial nephrectomy

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Introduction
The use of computer navigation systems is a new and actively explored method used for surgical procedures concerning the abdominal and retroperitoneal organs. In this paper, we propose an original hardware – software complex, which forms a virtual body model, based on preoperative computer tomography data, transmitted to the operating screen monitor using a surgical navigation system, involving a mechanical digitizer.

Material and methods
During a laparoscopic procedure, a three-dimensional (3D) model of a kidney with a tumor was used to obtain additional information on the primary or secondary monitor or for combining the virtual model and video images on the main or additional monitor in the operating room. This method was used for laparoscopic partial nephrectomy, where twelve patients were operated with an average age of 45.4 (38–54) years, with clear cell renal cell carcinoma size 27.08 (15–40) mm.

Results
All patients successfully underwent laparoscopic partial nephrectomy with intraoperative navigation. The mean operative time was 97.2 (80–155) minutes, warm ischemia time – 18.0 (12–25) minutes. Selective clamping of segmental renal arteries was performed in 7 (58.3%) cases, in the remaining 5 (41.6%) cases the renal artery was clamped. There were no serious complications. The average duration of hospital stay was 7.0 (5–10) days.

Conclusions
Preliminary results of our clinical study have shown the success of 3D modeling for qualitative visualization of kidney tumors in the course of surgical intervention, both for the surgeon and for the patient to understand the nature of the pathological process.

Key Words: 3D modeling ‚ computer navigation system ‚ laparoscopic partial nephrectomy

INTRODUCTION
Intraoperative three-dimensional (3D) navigation based on preoperative computed tomography (CT) data is actual for laparoscopic surgery on retroperitoneal space. The 3D model forms the best image of the organ and then complex images of a virtual model with the real images on the screen are obtained during the operation. This technique of augmented reality is actively being explored [1, 2]. The undoubtable advantage of this methodology is the better orientation of the surgeon in the operative field, which is especially important throughout the educational process of surgeons [3]. The possibility of applying the models/images in real time, reliability and precision applications of virtual and real objects are important for the usual requirement applicable to such systems.

In this article, we present the original hardware – software complex ‘Volga-M’ [4] that allows the creation of a 3D model rendered from CT scan data, in order to perform preoperative planning of surgery using virtual models on the screen, and initial clinical trials of intraoperative navigation during laparoscopic partial nephrectomy.
MATERIAL AND METHODS

In the Volga State Technical University and Republic- lican Clinical Hospital of Yoshkar-Ola of the Repub- lic of Mari El, a hardware – software complex called ‘Volga-M’, consisting of a computer and a mechani- cal digitizer combined with a laparoscope and a video camera was developed. The program ‘Volga-M’ allows for the formation of a 3D model of a surgical zone of interest obtained from CT data. In order to form a 3D model, a contour of a segmented image should be selected. The contour tracking includes a series of sequential image processing, resulting in the formation of a 3D model of the kidney and tumor at different angles [5]. Finally, the 3D model of the kidney formed with the translucent paren- chyma in order to demonstrate the internal structure of the organ. Patients with kidney tumors were selected as a test group (Figure 1). The obtained models of the organs were looked at and discussed with patients and their relatives in order to explain the nature of the disease and planned surgical procedure.

We used a mechanical digitizer, combined with a laparoscope and video camera head during endo- scopic surgery for combining the images of the 3D model with video images on the screen in the operating room [4]. The image of the virtual organ in the corresponding projections according to the location of the real camera was transferred to the main or to the additional monitor.

The trial obtained the approval of the local Eth- ics Committee of the Republican Clinical Hospital and voluntary informed consent was obtained from the patients. Nine patients, among whom 6 (50%) were men and 6 (50%) were women, with a mean age of 45.4 (38–54) years underwent standard clinical examination, including spiral CT scan, the results of which were recorded in the DICOM system. CT was performed using the Siemens ‘Sonotom 3000’ or Philips ‘Brilliance 64’ scanners using ‘Ul- travist-370’ contrast in the standard doses, with the kidney as the target retroperitoneal organ. All pa- tients presented with renal cancer T1N0M0. Using the original product ‘Volga-M’ we formed 3D models of the surgical zone of interest - the kidney with the tumor and blood vessels. The 3D models of the kid- neys with the tumors were shown to patients for the better understanding of the nature of their lesions, including their localization and size and planned surgical procedure.

During the preoperative planning, the selection of vessels supplying the segment containing the tu- mor were performed and marked most convenient for their temporary clamping. Virtual removal of the kidney tumor was performed, the results of which could later be compared with video of the real operation.

All patients underwent standard transabdominal laparoscopic partial nephrectomy, with mobilization of the relevant surrounding intestines. Selecting of kidney blood vessels, if possible to the segmental level, and clamping of a segmental or renal artery with respect to warm ischemia time, was performed. The kidney tumor was resected and hemostatic su- tutures were administered.

The trial studied demographic, intraoperative and postoperative data of patients in addition to the duration of operation, including the time of warm ischemia, and postoperative data including histopa- thology results, surgical margins and postoperative complications.

RESULTS AND DISCUSSION

All patients successfully underwent laparoscopic partial nephrectomy. Selective clamping of segmental renal arteries was performed in 7 (58.3%) cases, in the remaining 5 (41.6%) cases the renal artery was clamped. The renal pelvis was not opened in all cases. For hemostatic purposes, the parenchyma was sutured using a blanket stitch on plastic clips. The warm ischemia time was 18.0 (12–25) minutes. Average duration of the procedures was 97.2 (80–155) minutes. Average blood loss amounted to 207.5 (100–400) ml. In the postoperative period, early mo- bilization of the patient was conducted. Serious com- plications according to the Clavien classification [6] in the postoperative period were not observed. Patient no. 6 presented with a transient elevation of serum creatinine, however, this did not require any special treatment (G1). Patient no. 3 presented

Figure 1. 3D model of the kidney with a tumor of the lower pole.
with a urinary tract infection and the appropriate antibiotic therapy was administered (G2). All patients were diagnosed with clear cell carcinoma and there were no cases of positive surgical margins histologically. The average duration of treatment was 7.0 (5–10) days. Preoperative patient demographics, tumor characteristics, operative data, perioperative data, and pathologic outcomes for each patient are described in Table 1.

The volumetric model of the organ obtained using the program ‘Volga-M’ before surgery allowed for the preoperative planning of the upcoming partial nephrectomy by determining the localization of the tumor, its relation with kidney vessels and the renal pelvis, and identifying sections of the renal artery most convenient for vascular clamping. During the virtual removal of the tumor it was possible to observe the probable damage of the internal structures of the kidney, determine their location, and predict methods for eliminating future complications. In all cases of preoperative planning and discussion of its results, patients and their relatives understood the essence of the disease and the features of the forthcoming surgical intervention.

The video image of the virtual model of the kidney was visualized on the main or additional monitor screen together with the image obtained with a laparoscopic camera (Figure 2).

When using augmented reality technology, we combined the video image of the kidney tumor and a 3D model, with the demonstration the location of the renal vessels, segmental arteries, selected at preoperative planning a section of an artery to overlay vascular clamps, precise localization of the tumor (Figure 3).

The technique of combining the 3D model obtained from CT data with the intraoperative video image, allowed the surgeon to accurately represent not only the vessel architecture of the operated organ and its anatomy but also the location and spread of the kidney tumor, and its relationship with the surrounding blood vessels. Thanks to this, radical nephrectomy

Table 1. Patients’ demographic, intraoperative and postoperative data

| Patient N/Demographics | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | Mean | Standard deviation |
|------------------------|----|----|----|----|----|----|----|----|----|----|----|----|------|-------------------|
| Age                    | 45 | 49 | 39 | 51 | 46 | 38 | 54 | 47 | 44 | 41 | 48 | 43 | 45.42 | 4.78              |
| Sex                    | f  | m  | f  | f  | m  | f  | m  | f  | m  | m  | m  | f-6 | m-6               |
| BMI                    | 26 | 29 | 34 | 25 | 38 | 33 | 45 | 27 | 42 | 40 | 48 | 32 | 34.92             |
| Baseline renal function (EGCF) | 98 | 79 | 70 | 99 | 92 | 87 | 68 | 92 | 80 | 88 | 91 | 93 | 86.42 | 10.12             |
| Tumor size (mm)        | 22 | 30 | 21 | 15 | 32 | 20 | 31 | 25 | 40 | 33 | 31 | 25 | 27.08             |
| Operative data         |    |    |    |    |    |    |    |    |    |    |    |    |                   |
| Warm ischemic time (min) | 12 | 18 | 16 | 25 | 24 | 15 | 18 | 14 | 14 | 17 | 25 | 18 | 18.0              |
| Operative time (min)   | 80 | 155| 100| 90 | 95 | 105| 90 | 110| 85 | 95 | 80 | 97.92             |
| Blood loss (ml)        | 200| 300| 150| 100| 400| 250| 100| 300| 200| 110| 250| 130| 207.5             |
| Perioperative data      |    |    |    |    |    |    |    |    |    |    |    |    |                   |
| Hospital stay (d)      | 5  | 6  | 7  | 6  | 10 | 7  | 8  | 6  | 7  | 6  | 9  | 7  | 7.0               | 1.41              |
| Clavien complications  | -- | -- | G2UTI | -- | -- | G1tES | -- | -- | -- | -- | -- | -- |                   |
| Pathologic data        | T1a| T1b| T1b| T1a| T1b| T1b| T1b| T1a| T1b| T1a| T1b| T1a|                   |
| Tumor histology        | All–ccRCC4                  |
| Margin status          | All–negative                |

BMI – body mass index; UTI – urinary tract infection; tESC – transient elevation of serum creatinine; ccRCC – clear cell renal cell carcinoma

Figure 2. Demonstration of the 3D model on the surgical monitor.
fully applied the technology of augmented reality during robotic partial nephrectomy using an overlay of a reconstructed 3D tomography video of the image in real time [17].

In our study, we developed our own method of forming virtual models based on preoperative CT studies and integration of the images of the virtual model and the real organ – the kidney with the tumor. Further experimental work is planned in order to improve the quality of the image and automatic segmentation of organ images, adapt the virtual model to print on a 3D printer, and improve the integration of the 3D model to video image. Currently, research is aimed at pairing real and virtual video when performing endoscopic operations on the retroperitoneal organs in real time.

CONCLUSIONS

The software product ‘Volga-M’ allows the creation of a virtual three-dimensional model of the surgical zone or chosen organ based on data received from any CT scan. A 3D model of the marked organ can be successfully used for planning a surgical procedure or as a tool for explaining the procedure to the patient. Preliminary results of this study demonstrate the possibility of successful use of our hardware – software complex and 3D models for visualization of the affected organ during surgery, which is especially important in organ-preserving urologic procedures, such as laparoscopic partial nephrectomy.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.
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