

Virtual and Augmented Reality Systems for Renal Interventions: A Systematic Review

Felicitas J. Detmer, Julian Hettig, Daniel Schindele, Martin Schostak, Christian Hansen

***Abstract*—**
Purpose **Many virtual and augmented reality systems have been proposed to support renal interventions. This paper reviews such systems employed in the treatment of renal cell carcinoma and renal stones.**
Methods **A systematic literature search was performed. Inclusion criteria were virtual and augmented reality systems for radical or partial nephrectomy and renal stone treatment, excluding systems solely developed or evaluated for training purposes.**
Results **In total, 52 research papers were identified and analyzed. Most of the identified literature (87%) deals with systems for renal cell carcinoma treatment. Forty-four percent of the systems have already been employed in clinical practice, but only 20% in studies with ten or more patients. Main challenges remaining for future research include the consideration of organ movement and deformation, human factor issues, and the conduction of large clinical studies.**
Conclusion **Augmented and virtual reality systems have the potential to improve safety and outcomes of renal interventions. In the last ten years, many technical advances have led to more sophisticated systems, which are already applied in clinical practice. Further research is required to cope with current limitations of virtual and augmented reality assistance in clinical environments.**

***Index Terms*—Augmented Reality, Virtual Reality, Nephrectomy, Renal Interventions, Image-Guided Surgery**

I. Introduction

THE kidney is an important organ of the urinary system controlling the body's fluid and electrolyte balance and eliminating waste products. It can be affected by diseases such as nephrolithiasis and renal cell carcinoma (RCC), which are briefly described in the following.

A. Renal Diseases and Interventions

Nephrolithiasis, the formation of renal stones, is a common disease affecting about 5-10 % of the population worldwide with a prevalence of 9 % in the United States in 2012 [1], [2]. A second important pathology of the kidney is RCC. It is the ninth most common cancer, with 61,560 estimated new cases in the United States in 2015 [3], [4].

Manuscript received October 20, 2016; revised April 17, 2017; accepted August 11, 2017; date of current version September 1, 2017.

F. J. Detmer is with the Department of Bioengineering, George Mason University, Fairfax, VA, 22030 USA and was with the Institute for Simulation and Graphics, Department of Computer Science, Otto-von-Guericke University Magdeburg, Germany (e-mail: fdetmer@gmu.edu).

J. Hettig and C. Hansen are with the Institute for Simulation and Graphics, Department of Computer Science, Otto-von-Guericke University Magdeburg, Germany (e-mail: hettig@isg.cs.uni-magdeburg.de; hansen@isg.cs.uni-magdeburg.de).

D. Schindele and M. Schostak are with the Clinic of Urology and Pediatric Urology, University Hospital of Magdeburg, Germany (e-mail: daniel.schindele@med.ovgu.de; martin.schostak@med.ovgu.de).

Treatment options include radical nephrectomy (RN), partial nephrectomy (PN) or ablation techniques, such as radio frequency ablation (RFA) [5]. For small to medium-sized renal tumors, nephron-sparing tumor resection is recommended [6] due to comparable oncological outcome while better preserving renal function compared to RN [7], [8]. Ablation techniques are considered as a treatment option for patients who are not eligible for resection techniques [9], [5]. Minimally invasive approaches have several advantages in comparison to open surgeries, such as shorter hospital stay and faster recovery. They are also of importance for renal stone and RCC treatment. Non-invasive or minimally invasive approaches are already standard in treatment of nephrolithiasis, and minimally invasive therapies are gaining increasing importance in RCC treatments. A laparoscopic approach is already considered the standard of care for RN [10]. Laparoscopic partial nephrectomy (LPN) and robot-assisted partial nephrectomy (RAPN) have gained increasing importance for nephron-sparing surgery during the last years (especially for PN) [11] since the first LPN in 1991 [12], [13]. Compared to open partial nephrectomy (OPN), LPN is associated with decreased operative blood loss and shorter hospital stays [14].

In minimally invasive procedures, the direct view of the operation field is replaced by information from imaging systems, such as intraoperative ultrasound (IOUS), fluoroscopy, or endoscopic video. This change is generally accompanied by challenges due to a reduced haptic feedback and a limited field of view. Particularly in LPN, the tumor detection by IOUS is challenging, especially for intraparenchymal tumors or isoechoic tissue [15]. To reduce bleeding and achieve a clear (endoscopic) view during tumor resection, renal or higher-order arteries are clamped, leading to warm ischemia, which is related to postoperative renal impairment [16]. Therefore, two important aims consist of reducing the warm ischemic time or to perform tumor resection without hilar clamping. In percutaneous nephrolithotomy (PCNL), difficulties include finding a trajectory to the target stone while avoiding risk structures. In order to assist the surgeon in performing safe renal interventions, several computer assistance systems have been developed addressing these challenges. Another aspect, contributing to the role of computer assistance, is the shift for procedures, such as PCNL from interventional radiologists to urologists. This leads to requirements of additional training and assistance for image-guided surgeries [17], [18].

B. Virtual and Augmented Reality

Many computer assistance systems rely on virtual reality (VR) or augmented reality (AR) approaches. This review aims to provide a comparative and critical overview of those systems that are used for the renal interventions described above. The focus on these interventions results from the predominance of these areas for VR/AR applications and is examined further in the discussion section of this paper.
VR is described as "the use of computer modeling and simulation that enables a person to interact with an artificial three-dimensional (3D) visual or other sensory environment" [19]. Whereas VR therefore relies on purely virtual environments, AR "allows the user to see the real world, with virtual objects superimposed upon or composited with the real world" [20]. Both aspects are used for clinical purposes by enabling the presentation of additional information pre- and intraoperatively. Preim and Botha [21] provide a comprehensive overview of medical VR/AR displays. The scope of this review covers VR and AR systems for support in renal interventions with focus on PN, RN, PCNL and lithotripsy. VR is in this context considered as a virtual scene (e.g. virtual 3D model) that can be manipulated by human-computer interaction. The immersive character, which is further described in [19] as "VR applications immerse the user in a computer-generated environment that simulates reality through the use of interactive devices [...] worn as goggles, headsets, gloves, or body suits", is not considered essential. Here, VR systems can therefore be either "simple" 3D planning models of the kidney or systems that can be used to perform complete virtual surgeries.

C. Previous Work

VR and AR systems play an important role in assistance for renal interventions, the former especially for precise planning, the latter intraoperatively to provide enhanced 3D orientation. Several reviews have been published previously dealing with AR support for urological interventions. Some of them cover general advances in image-guided urological surgery, including, but not focusing on, AR approaches for kidney interventions [22], [23], [24]. Najmaei et al. [25] discuss AR for hepatic and renal interventions encompassing laparoscopic and percutaneous treatments. Rassweiler et al. [26] review European projects dealing with AR for navigation in prostate and kidney interventions. Nakamoto et al. [27] present AR approaches in abdominal and urological laparoscopic surgery covering methods applied in PN surgeries. Nicolau et al. [28] review different aspects of AR for laparoscopic surgical oncology, such as RCC treatment. A review describing different approaches for AR in PN with respect to registration and tracking in detail is given by Hughes-Hallett et al. [29]. Reviews dealing with VR applications in the context of laparoscopic or percutaneous interventions address VR used in training systems rather than for planning support [18], [30].

In this review, a search strategy was selected including VR and AR systems. In contrast to the previously published reviews, the systems are discussed both with respect to VR and AR. Furthermore, also technical approaches that have not been applied in clinical practice yet but are promising for future VR or AR systems are also included.

The subsequent parts of this paper are structured as follows: First, the literature search strategy together with its inclusion criteria is described. Second, the results are presented by giving an overview of systems for assistance in RN, PN, and renal stone treatment as well as of approaches dealing with challenges of segmentation and registration. In addition, the current state of clinical evaluation and studies dealing with human factors concerning AR are described. Finally, the results of the literature review are discussed.

II. METHODS

In the following, the literature search strategy together with the inclusion and exclusion criteria will be presented.

A. Search Strategy

A systematic literature search spanning from January 2005 to June 2016 was conducted using the database PubMed. PRISMA guidelines were followed [31]. The search-term *((((("computers"[MeSH Terms] OR "computers"[All Fields] OR "computer"[All Fields]) AND assisted [All Fields]) OR ((augmented OR virtual) AND reality))) AND (("nephrectomy"[MeSH Terms] OR "nephrectomy" [All Fields]) OR ("lithotripsy" [MeSH Terms] OR "lithotripsy" [All Fields]) OR nephrolithotomy[All Fields]))* was applied.

Based on the titles and abstracts, literature was selected and reviewed in detail by two reviewers (F.D., J.H.). Cross-references and further literature from an excerpt of a Google Scholar search, using the search-term *(("computer assisted" OR "augmented reality" OR "virtual reality") AND (nephrectomy OR nephrolithotomy OR lithotripsy))*, were additionally included depending on their relevance for the review's purpose.

B. Inclusion Criteria

Inclusion criteria were VR/AR systems used for assistance in planning and/or intraoperatively for guidance in one of the three defined kidney interventions:

- nephrectomy or partial nephrectomy,
- intracorporal lithotripsy, and
- percutaneous nephrolithotomy (PCNL).

Literature dealing with systems solely utilized for training purposes or their evaluation was excluded. Furthermore, systems and segmentation or registration approaches designed for more broader purposes (e.g. laparoscopic interventions) were included when their evaluation was performed on data from kidney interventions. The selected literature was restricted to English language. Reviews and letters were excluded. Furthermore, only literature published from January 2005 to July 2016 was considered.

III. RESULTS

The results of the search strategy are summarized in Fig. 1. A total of 319 references resulted from the PubMed database search using the previously defined search term. From these,

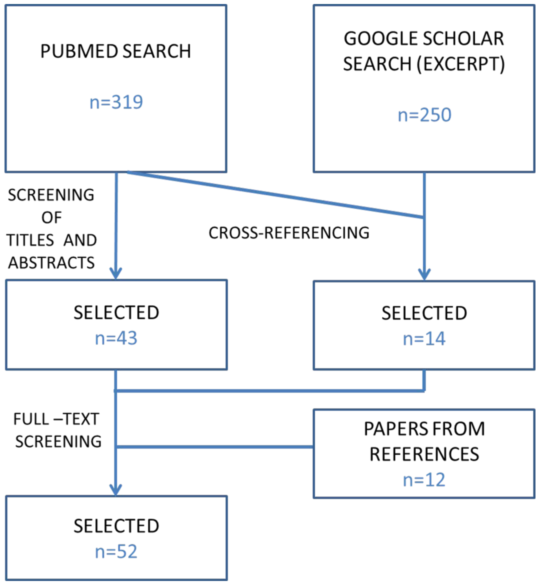

Fig. 1. Literature search strategy: A literature search was performed in PubMed and extended by an excerpt of Google Scholar results. After title and abstract screening, full texts of the selected literature were analyzed. Based on the defined inclusion criteria, 52 papers were selected.

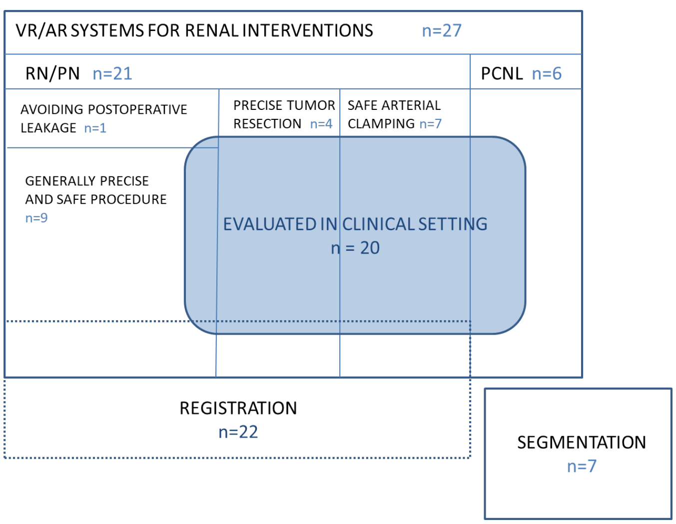

Fig. 2. Overview of identified systems and methods from the literature.

43 were selected for detailed screening and enhanced by 26 additional publications from cross-references including results from the Google Scholar search. Finally, 52 references were chosen as a basis for this review. Figure 2 provides an overview of the topics that were addressed by the identified literature.

A. Clinical Objectives

An overview of systems for surgical treatment of RCC and renal stones is given in Table I and Table II, respectively. In general, the clinical objective of VR/AR systems for kidney interventions is the improvement of patient outcome. The following, more specific objectives are addressed in the literature, including VR/AR assistance for:

- precise tumor resection [32], [33], [34], [35],

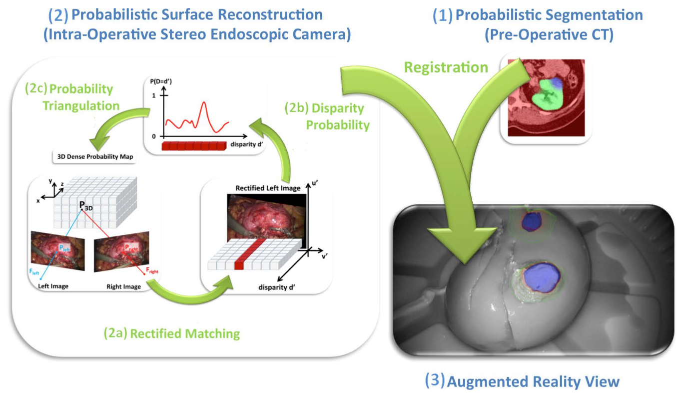

Fig. 3. Scheme of approach for augmentation of endoscopic video by tumor margins incorporating uncertainties from segmentation [32].

- safe renal clamping [36], [37],
- selective arterial clamping [38], [39], [40], [41], [42], and
- avoidance of postoperative leakage due to open urinary tract [43],

in the case of RCC treatment, and

- needle trajectory guidance [44], [45], [46], [47], [48], [49], [50]

for renal stone treatment. These clinical objectives are addressed both by VR and AR systems. They are described as follows, ordered by the clinical objectives. In addition, research papers not addressing one of these specific clinical objectives are presented subsequently.

1) Precise Tumor Resection: Precise tumor resection achieving negative resection margins while preserving a maximum of healthy tissue is one important step in PN. It requires an exact tumor delineation. Several AR systems directly address this challenging step.

Three systems are based on the registration of preoperative CT data with data from endoscopic videos. Ukimura and Gill [35] visualize information from preoperative CT on the endoscopic video by superimposing tumor margins using a color overlay that encodes the distance from the tumor. The accuracy is described as sufficient without presenting information on the evaluation procedure of the system. Amir-Khalili et al. [32] propose a system for enhancing stereo endoscopic images by overlay of tumor margins. Different contours encode information about their uncertainties resulting from segmentation. Their approach is based on semi-manual probabilistic segmentation of kidney and tumor boundaries from preoperative CT data (see Fig. 3).

For registration of the segmentation result, semi-automatic rigid registration combined with local scaling followed by a non-linear B-spline registration step is applied. In their work, different visualization methods were evaluated by urologists using lamb kidneys. The most appealing one provides information about the tumor boundary of highest probability together with the local confidence by using a color-coded contour (see Fig. 4). Finally, Chen et al. [33] generate a 3D model from preoperative CT images for precise planning, including morphometry and surgery simulation. Intraoperatively, the 3D

TABLE I

VR/AR SYSTEMS FOR ASSISTANCE OF **NEPHRECTOMY**, I.E. RADICAL NEPHRECTOMY (RN) AND PARTIAL NEPHRECTOMY (PN), ORDERED BY CLINICAL OBJECTIVES. IDENTIFIED PROCEDURES ADDRESSED BY THE SYSTEMS INCLUDE OPEN PARTIAL NEPHRECTOMY (OPN), LAPAROSCOPIC PARTIAL NEPHRECTOMY (LPN), ROBOT-ASSISTED PARTIAL NEPHRECTOMY (RAPN) AND LAPAROSCOPIC RADICAL NEPHRECTOMY (LRN).

	Procedure	Clinical Objective	Technical Approach	VR/AR	Evaluation
Amir-Khalili et al. 2013 [32]	RAPN	Precise tumor resection	Augmentation of endoscopic view by virtual tumor margins; visualization of segmentation uncertainty	AR	Ex vivo: lamb kidneys; alignment error
Chen et al. 2014 [33]	LPN	Precise tumor resection for intrarenal tumors	Augmentation of endoscopic view by 3D model; manual registration	AR	In vivo: 15 patients undergoing LPN
Cheung et al. 2010 [34]	LPN	Precise tumor resection	Augmentation of stereoscopic endoscopic view by IOUS image; manual registration combined with tracking	AR	In vitro: phantom study
Ukimura and Gill 2008 [35]	LPN	Precise tumor resection	Augmentation of endoscopic view by virtual tumor margins; color-coded margin zones	AR	In vivo: 1 patient
Amir-Khalili et al. 2014 [36]	RAPN	Safe renal clamping	Highlighting of occluded vessels near renal hilum in endoscopic video	AR	Retrospective: 8 RAPN cases
Amir-Khalili et al. 2015 [37]	RAPN	Safe renal clamping	Highlighting of occluded vessels near renal hilum in endoscopic video	AR	Retrospective: 15 RAPN cases, clinical user study
Furukawa et al. 2014 [38]	RAPN	Safe selective arterial clamping	3D model displayed below endoscopic video on robotic console	VR	In vivo: 17 patients undergoing RAPN
Komai et al. 2014 [39]	LPN/ OPN	Safe selective arterial clamping	3D model for planning and intraoperative guidance	VR	In vivo: 26 patients undergoing PN
Ukimura and Gill 2012 [40]	LPN/ RAPN	Safe selective arterial clamping	3D model for planning and intraoperative guidance	VR	In vivo: 4 patients undergoing LPN/ RAPN
Wang et al. 2015 [41]	LPN	Safe selective arterial clamping	Augmentation of endoscopic view by 3D model; manual registration	AR	In vivo: 35 patients undergoing LPN, retrospective
Isotani et al. 2015 [42]	RAPN	Safe selective arterial clamping	Preoperative simulation of PN and intraoperative display of 3D model below endoscopic video	VR	In vivo: 20 patients undergoing RAPN, retrospective
Ueno et al. 2014 [43]	LPN	Avoiding postoperative leakage due to open urinary tract	3D model with virtual resection plane for planning	VR	Retrospective: 5 patients undergoing LPN
Makiyama et al. 2012 [51]	LRN/ LPN	Generally precise and safe PN, especially for patients with rare anatomical conditions	VR-simulator based on individual patient computed tomography (CT) data for “rehearsal” surgeries	VR	In vivo: 13 patients undergoing LPN/ LRN and pyeloplasties [52]
Baumhauer et al. 2008 [53]	LPN	Generally precise and safe PN	Augmentation of endoscopic video by 3D model from preoperative CT; intraoperative imaging for registration	AR	In vitro: porcine kidney model
Teber et al. 2009 [54]	LPN	Generally precise and safe PN	Augmentation of endoscopic video by 3D model from preoperative CT; in vivo manual registration	AR	In vitro: 10 porcine kidneys; in vivo: 10 patients undergoing LPN
Nakamura et al. 2010 [55]	LPN, LRN	Generally precise and safe PN, RN	Augmentation of endoscopic video by intraoperatively reconstructed 3D model; manual registration	AR	In vivo: 2 patients undergoing LPN, 3 LRN
Su et al. 2009 [15]	RAPN	Generally precise and safe PN	Augmentation of endoscopic video by 3D model from preoperative CT; manual initial registation	AR	Post-processing of video data from 2 RAPN
Altamar et al. 2011 [56]	RAPN	Generally precise and safe PN	Registration of endoscopic video with preoperative CT; surface-based registration by manual tracking	AR	In vivo: RAPN procedures
Pratt et al. 2015 [57]	RAPN	Generally precise and safe PN	Augmentation of endoscopic video by laparoscopic IOUS image; tracking of IOUS probe	VR	In vivo: 1 RAPN
Lasser et al. 2012 [58]	RAPN	Generally precise and safe PN	3D model for planning and display below endoscopic video on robotic console	VR	10 patients undergoing RAPN
Hughes-Hallett et al. 2014 [59]	RAPN	Generally precise and safe PN	3D model for planning and display below endoscopic video on robotic console	VR	In vivo: 5 patients undergoing RAPN

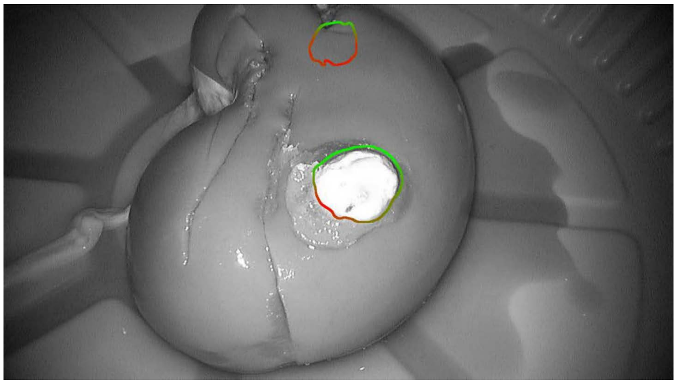

Fig. 4. AR view of tumor margins on ex vivo lamb kidney. Uncertainty is encoded into the tumor boundary ranging from certain (green) to uncertain (red) [32].

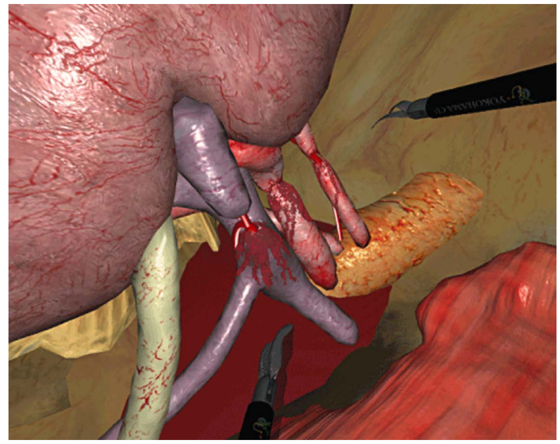

Fig. 5. View of VR environment of in simulator for "rehearsal" laparoscopic renal surgery (here: hemostasis training) [51].

model is manually registered with the endoscopic video based on an accuracy verification with IOUS.

An AR system based on the registration of stereoscopic endoscope and IOUS images is described by Cheung et al. [34]. The system is realized by electromagnetically tracking the IOUS probe and the endoscope. A phantom study demonstrates the system usability and an improvement in resection planning times using the fused view.

2) Safe Selective Arterial/Renal Clamping: Besides support for precise tumor resection, several groups address support for artery clamping. Artery clamping is performed by clamping either the renal artery (hilar clamping) or higher-order vessels supplying tumor-containing segments, i.e., selective artery clamping, also known as segmental artery clamping [60], clampless PN [39] or "Zero ischemia" PN [40]. Several systems have been developed to address challenges related to artery clamping.

Amir-Khalili et al. [36], [37] use an adapted phase-based video magnification technique to highlight hidden vessels near the renal hilum in the endoscopic video. The method was evaluated retrospectively on videos from RAPN cases, and the vessels were successfully detected in 13 of 15 cases. Problems occurred during the automatic segmentation process when motion of tools was present in the scene. An evaluation of the effect of the proposed method on the identification of hidden vessels by surgeons revealed a shorter vessel detection time for junior surgeons (no change for experienced surgeons), whereas the detection rate was only minimally affected both in the cases of junior and experienced surgeons. Surgeons used the tool mainly to confirm their own vessel localization, which they reported as beneficial.

While Amir-Khalili et al. address difficulties occurring during hilar dissection and renal artery clamping, several systems have been developed with the aim to assist in identifying targeted tertiary and high-order arterial branches for selective artery clamping. 3D models with extracted tumor and target vessels are used for preoperative planning including surgery simulations [39], [41], [42] and intraoperative guidance by displaying them below the endoscopic view on the console of the DaVinci robotic system using the system's TilePro function [38], [42] or on a separate screen during LPN [39], [40]. Manual registration of the 3D model with the 3D endoscopic video is performed intraoperatively to generate a fused view supporting the identification of the target vessels [41].

3) Avoiding Postoperative Urine Leakage: One potential complication occurring after PN is postoperative urine leakage due to an open urinary tract. Ueno et al. [43] address this problem with a VR system for predicting the presence of an open urinary tract. A virtual resection plane is created in a 3D model reconstructed from preoperative CT images. The application of resection planes for different amounts of resection margins is used to predict whether and at which margin the urinary tract would be open. Retrospective evaluation on five LPN cases showed that the predicted and the actual intraoperative outcome were consistent in all but one patient. The method of preoperative surgical simulation proposed by Isotani et al. [42] can further be used for predicting an opening of the collective system. Here, the preoperative prediction was correct in 19 out of 20 RAPN cases. Postoperative urine leakage rates are reported as 2-2.4 % for LPN and 1.6 % for RAPN [61], [62]. The studies by Ueno and Isotani show that opening the urinary tract can be predicted by the presented technologies. Whether the actual risk of postoperative leakage can be not only predicted, but also reduced by those systems, necessitates further evidence.

4) Generally Precise and Safe Partial Nephrectomy: To assist preoperative planning of nephron-sparing surgeries for patients with rare anatomical conditions, Makiyama et al. [51] developed a VR simulator based on individual patient CT data enabling virtual "rehearsal" surgeries prior to the actual intervention. For the surgery simulations, a deformation model is applied on a tetrahedral data set generated by a finite element method (FEM) from the semi-automatically segmented CT data. A haptic device is incorporated in the system to generate haptic feedback. Fig. 5 visualizes part of the VR environment.

In addition, other AR systems without a specific clinical aim are described. Baumhauer et al. [53] propose a navigation system for LPN. Segmented data from preoperative CT images are displayed as an AR overlay on the endoscopic video. Deformation of the kidney is taken into account by the use of custom-designed navigation aids inserted into kidney and intraoperative CT cone beam imaging. The same principle is applied by Teber et al. [54]. Fully automatic registration is realized in the in vitro experiments, whereas manual navigation by orientation based on anatomic landmarks is used for the in vivo cases. Nakamura et al. [55] enhance the endoscopic video by manual fusion with intraoperatively reconstructed 3D models. Su et al. [15] impose 3D kidney models onto endoscopic videos during RAPN. For augmentation, the 3D kidney model is imported onto the endoscopic video segment and manually calibrated to achieve visual fit. A surface-based tracking technique allows for subsequent automatic tracking of coarse movements to automatically adjust the overlay. Organ deformation is not incorporated. Altamar et al. [56] augment the endoscopic view with surfaces generated from preoperative CT in RAPN by surface-based registration. Determination of the surface points on the kidney is realized by manually scanning the kidney surface with a robotic instrument during surgery and simultaneously tracking its position. A different AR approach is presented by Pratt et al. [57]. Here, the endoscopic video is augmented by the image obtained from laparoscopic IOUS. Optical markers attached to the laparoscopic IOUS probe are used for the registration between stereo endoscope and IOUS image.

Similar to Furukawa et al. [38], Hughes-Hallett et al. [59] and Lasser et al. [58] display a 3D model generated from preoperative CT below the endoscopic video on a DaVinci robotic console using the TilePro function of the DaVinci system. Prior to surgery, extensive planning including virtual manipulation and removal of target structures is performed based on the 3D model [58]. Intraoperative manipulation of the model is possible via a tablet computer attached near the console, and the manipulated image is replicated on the console view [59].

5) Safe Trajectory Finding for Renal Stone Treatment: Whereas the treatment of RCC is addressed by many VR/ AR systems, six such systems were identified for renal stone treatment (cf. Table II). They aim to assist in safe trajectory finding.

Mozer et al. [44] perform surface-based registration of 3D models from preoperative CT with IOUS for intraoperative needle guidance. Segmentation of the kidney from the IOUS data is performed manually and both the IOUS probe and the needle are tracked optically. In a later study [45], this method is used to superimpose the puncture tract from the IOUS image on the fluoroscopic image obtained at the beginning of the procedure. Li et al. [46] use a 3D model generated from preoperative magnetic resonance imaging (MRI) for trajectory planning and intraoperative augmentation of real-time IOUS. The needle and the IOUS probe are optically tracked and a virtual model of the needle is displayed in the fused image. To take organ deformation due to breathing into account, only IOUS slices at maximum exhalation obtained through an optical tracking-based respiratory gating technique are used for overlay of the 3D model on the IOUS image and subsequent puncture. Accuracy evaluation with four volunteers resulted in a mean target registration error (TRE) of 3.53 mm.

Another navigation system based on optical tracking is introduced by Oliveira-Santos et al. [47]. Unlike the previously described systems, the preoperative CT scan is registered to the patient using fiducial markers, and not based on intraoperatively obtained image data. Li et al. [49] address the challenge of obtaining an appropriate access to the renal stones in the case of complex anatomical or pathological conditions. Precise preoperative planning based on a 3D model reconstructed from preoperative CT images is supported by incorporating a virtual puncture needle into the model. Intraoperatively, the model is used to identify the planned insertion point based on anatomical landmarks and provide detailed anatomical information during the lithotripsy procedure.

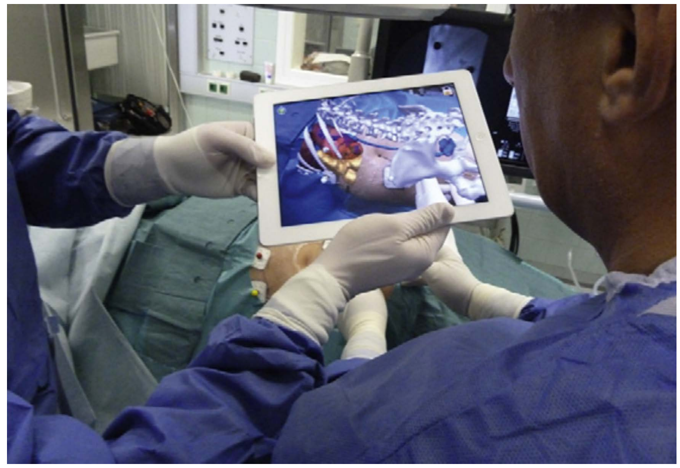

Fig. 6. IPad-assisted marker-based navigation of percutaneous access to the kidney. Figure adapted based on [48].

An AR system described first by Rassweiler et al. [48] and later in more detail in [50] is used to support the percutaneous access by overlaying a 3D model onto the image from a tablet camera (see Fig. 6).

Registration is based on fiducial markers and camera calibration. The conducted phantom study demonstrated a decrease in puncture time and radiation exposure for urology trainees in comparison to other modalities, i.e., US and fluoroscopy without AR assistance. However, no major improvements were found for experienced urologists. Evaluation on a phantom revealed a decreased puncture time and radiation exposure for the urology trainee in comparison to other image modalities, but no major improvements in case of an experienced urologist.

B. Intraoperative Image Segmentation

Segmentation of structures from intraoperatively acquired images is one crucial step for many VR/AR guidance systems, e.g., it is the basis for non-fiducial based registration techniques. In the literature, intraoperative segmentation from IOUS and endoscopic images is described. An overview of these approaches is given in Table III .

Segmentation from IOUS images is challenging due to the appearance of attenuation, speckle, shadows and signal dropout [70]. Three methods dealing with segmentation from IOUS images were identified in the literature. First, Xie et al. [63] developed a texture and shape prior-based method for segmentation of the kidney in two-dimensional (2D) IOUS

TABLE II
VR/AR SYSTEMS FOR ASSISTANCE OF **RENAL STONE TREATMENT**, I.E. PERCUTANEOUS NEPHROLITHOTOMY (PCNL), AS NO SYSTEMS FOR LITHOTRIPSY WERE IDENTIFIED IN THE LITERATURE.

	Procedure	Clinical Objective	Technical Approach	VR/AR	Evaluation
Mozer et al. 2005 [44]	PCNL	Needle trajectory planning and guidance	3D model for preoperative planning and intraoperative guidance; display of virtual needle; optical tracking	VR	Ex vivo: phantom study
Mozer et al. 2007 [45]	PCNL	Needle trajectory guidance	Augmentation of fluoroscopic image by puncture tract obtained from IOUS needle guide; optical tracking	AR	Ex vivo: phantom study; in vivo: 1 patient
Li et al. 2012 [46]	PCNL	Needle trajectory guidance	Augmentation of IOUS image by 3D model from preoperative MRI; respiratory gating	AR	Ex vivo: phantom study
Oliveira-Santos et al. 2010 [47]	PCNL	Needle trajectory guidance	Augmentation of 3D model from preoperative CT by puncture tract; optical tracking	AR	In vitro: phantom study
Li et al. 2013 [49]	PCNL	Needle trajectory planning and guidance	3D model for preoperative planning and intraoperative guidance; display of virtual needle	VR	In vivo: 5 patients with complex stones undergoing PCNL
Rassweiler et al. 2012 [48], Müller et al. 2013 [50]	PCNL	Needle trajectory guidance	Augmentation of tablet camera view by 3D planning model from preoperative CT; marker-based registration	AR	in vivo: 2 patients; ex vivo: phantom study

TABLE III
LITERATURE DEALING WITH **INTRAOPERATIVE IMAGE SEGMENTATION** FOR VR/AR SYSTEMS ORDERED BY IMAGE MODALITY.

	Modality	Objective	Method
Xie et al. 2005 [63]	IOUS	Introduction of kidney segmentation method	Semi-automatic approach; texture and shape prior based method
Ahmad et al. 2006 [64]	IOUS	Introduction of kidney tumor segmentation method	Semi-automatic approach; slice-based segmentation using tracked IOUS probe; discrete dynamic contour method
Yang et al. 2012 [65]	IOUS	Introduction of kidney segmentation method	Automatic approach; non-local total variation (NLTV) image denoising, distance regularized level set evolution (DRLSE) and shape prior
Nosrati et al. 2014 [66]	Laparoscopic video	Introduction of kidney/tumor segmentation method given its preoperative 3D model	Semi-automatic approach; mathematical model including priors about camera motion and kidney shapes
Nosrati et al. 2015 [67]	Laparoscopic video	Introduction of kidney/tumor segmentation method given its preoperative 3D model	Automatic approach; mathematical model including priors about camera motion and calibration corrections and kidney shapes
Nosrati et al. 2016 [68]	Laparoscopic video	Introduction of kidney/tumor and vessel segmentation method given its preoperative 3D model	Combination of method proposed in [37] with visual cue analysis and patient-specific deformation model
Rosa et al. 2011 [69]	Laparoscopic video	Introduction of segmentation method for calculi in urinary tract	Semi-automatic approach; region growing algorithm; seed point definition using centroid of a laser spot

images. They propose a two-sided convolution strategy for texture feature extraction combined with a deformable shape model constructed from a data set of training shapes. Segmentation is realized by an iterative procedure of updating parameters of the initially manually placed segmenting curve to minimize a texture-based energy function. Second, Ahmad et al. [64] describe a method for the segmentation of the 3D tumor surface from 2D IOUS. The surface is obtained by sweeping around the tumor with an optically tracked IOUS probe and applying a discrete dynamic contour algorithm for segmentation after initial manual selection of tumor boundaries. In a modified approach, relying on the assumption of a spherical or ovate tumor, a so-called "guide surface" is generated to support the generation of seed contours. A comparison of the two methods revealed more precise segmentation results for the unguided approach in comparison to a manually segmented gold standard. However, at the same time more user interaction is required. Third, Yang et al. [65] apply a distance regularized level set evolution (DRLSE) method [71] after nonlocal total variation (NLTV) denoising for kidney segmentation. Subsequent post-processing is based on shape priors obtained from a principal component analysis performed on a set of training shapes, and finally, if quantitative measures of the segmentation are below a defined threshold, an alignment model is applied to increase the shape space and yield higher accuracy in segmentation.

Besides methods for IOUS image segmentation, the segmentation of endoscopic images is important to enhance VR/AR systems. In this context, four relevant research papers were identified. Nosrati et al. [66] propose a method for the segmentation of an object in a 2D endoscopic image given its preoperative 3D model. After a manual alignment of the preoperative model with the 2D image, subsequent registration is realized by taking information on camera motion into account. In RAPN, the latter can be obtained from information about the position of the robotic arm. Non-rigid

Fig. 7. Examples of shape variations of a kidney and its two tumors after deformations used for segmentation in [67].

deformation is considered using information from a catalog of 3D deformation shapes (see Fig. 7).

A comparison to other segmentation algorithms demonstrates that incorporation of priors yields a more robust segmentation, e.g., in case of occlusions caused by instruments. In a further extension [67], the correction of camera calibration parameters (due to focus or zoom) is included in the method. In order to segment kidney and tumor tissue as well as the supplying vasculature, a combination of the method introduced in [37] and an extension of the approach presented in [67] is proposed [68]. Here, an energy function is minimized based on visual cues in the endoscopic video as well as a phase-based pulsation analysis. For segmentation of the structures of interest, information about patient-specific tissue properties is further incoporated via a deformation model used to generate patient-specific shape-models from preoperative 3D data. Fig. 8 illustrates this method.

It should be remarked that these approaches [66], [67], [68] demonstrate a natural overlap between the objectives of intraoperative image segmentation on the one hand, and registration and deformation handling on the other hand. Here, registration of a preoperative model with the intraoperative image is used for intraoperative image segmentation.

Finally, Rosa et al. [69] describe a method for the segmentation of renal stones in the endoscopic video for immediate support during lithotripsy. In their approach, they make use of the standard clinical situation that prior to lithotripsy a visible laser light is pointed on the renal stone for orientation of the laser beam subsequently used for stone destruction. The centroid of the laser spot is used as a seed for the applied region growing algorithm. During evaluation of the method on videos from ureteroscopy, 94% of the images were segmented correctly.

C. Intraoperative Registration and Deformation Handling

Accurate and robust registration is crucial for VR/AR systems, but can be difficult due to continuous organ movement and non-rigid organ deformation during surgery. Several technical approaches for intraoperative image registration and deformation handling are proposed (see Table IV). Constantly repeated manual image registration is computationally cheap but requires a lot of user interaction and cognitive effort. For example, several groups [33], [41], [54], [55] propose to align 3D planning models based on preoperative CT with laparoscopic video images while using anatomic landmarks for orientation. These systems require an additional surgical assistant performing the image registration [33], [41] or additional effort of the surgeon [54], [55]. Constantly repeated manual image registration techniques are mainly proposed in clinical studies [33], [41], [54], [55] because they are easy to implement and robust.

Furthermore, automatic or semi-automatic registration techniques are proposed to reduce interaction time during surgery. Baumhauer et al. [53] use real-time C-arm CT imaging combined with fiducials inserted into the target organ for deformation tracking and registration of the preoperative planning with the actual patient anatomy.

A less invasive approach consists in the implementation of feature-based tracking methods. Benincasa et al. [72] evaluate the performance of surface-based registration on different endoscopic views. Registration is performed using a rigid iterative closest point (ICP) algorithm [84]. The authors deduce that approximately 28% of the kidney surface is required to perform robust registration. Besides the amount of the visible surface, also the part of the kidney being visible has an influence on the robustness on the registration.

Ong et al. [73] propose a method of surface reconstruction for surface-based registration by using a holographic conoscope. Here, a 3D point cloud is obtained by moving an optically tracked conoscope across the surface. The video of of the endoscopic camera is subsequently used for texture mapping of this point cloud. An evaluation of this method on ex vivo porcine and human kidneys revealed a submillimetric accuracy as well as an improvement of accuracy with lower conoscope scanning speed. In contrast, the scan line density had no signifcant influence on the registration error determined by the use of fiducials.

An approach for registration of preoperative CT with laparoscopic IOUS images is described by Estepar et al. [74]. Here, a phase-correlation based approach is chosen with the aim of improving registration results when small shifts from initial registrations occur, especially out-of-plane alignment. The proposed method uses edge information between tissues with different acoustic properties and CT densities. An inherent limitation is the requirement of sufficient structural information in the IOUS image. The authors therefore propose for future work the development of an automatic method for frame selection. Evaluation on a phantom yields a root mean square error of less than 2.0 mm; registration is possible within a few seconds.

Edgcumbe et al. [75] introduce a miniaturized projector for intraoperative surface reconstruction, identification of tissue motion and augmentation of the surgical field. For surface reconstruction using a stereo laparoscope, the surface is scanned with a projected checkerboard pattern from different orientations and reconstructed by means of stereo triangulation. In case of a mono laparoscope, the projector is additionally visually tracked with the endoscope to determine its position for subsequent triangulation with the projector and endoscopic camera. When comparing both approaches in an in vivo porcine model, higher accuracies were achieved with the latter method. Furthermore, detection and visualization of surface motion from underlying vessels measured by visually tracking a projected checkerboard is demonstrated for the carotid artery,

TABLE IV

REGISTRATION TECHNIQUES FOR VR/AR SYSTEMS ORDERED BY TECHNICAL APPROACH (MANUAL REGISTRATION VS (SEMI-)AUTOMATIC REGISTRATION), ADDRESSING RADICAL NEPHRECTOMY (RN) AND PARTIAL NEPHRECTOMY (PN), I.E. LAPAROSCOPIC PARTIAL NEPHRECTOMY (LPN) AND OPEN PARTIAL NEPHRECTOMY (OPN). IF NOT STATED OTHERWISE, CT REFERS TO PREOPERATIVE CT.

	Procedure	Modalities	Objective	Method	Evaluation
Teber et al. 2009 [54]	LPN	Laparoscopic video, CT	Clinical evaluation of an AR-based navigation system	Intraoperative manual image registration by surgical assistant; optical tracking of fiducial on the kidney surface	In vitro: porcine kidneys; in vivo: 10 patients undergoing LPN
Nakamura et al. 2010 [55]	LPN, LRN	Laparoscopic video, CT	Evaluation of planning system (VR); clinical evaluation of AR navigation	Intraoperative manual image registration by surgeon, no tracking system used	In vivo: 2 patients undergoing LPN, 3 LRN
Chen et al. 2014 [33]	LPN	Laparoscopic video, CT	Evaluation of planning system (VR); clinical evaluation of AR navigation	Intraoperative manual image registration by surgical assistant; no tracking system used	In vivo: 15 patients undergoing LPN
Wang et al. 2015 [41]	LPN	Laparoscopic video, CT	Evaluation of planning system (VR); clinical evaluation of AR navigation	Intraoperative manual image registration by surgical assistant, no tracking system used	In vivo: 35 patients undergoing LPN
Baumhauer et al. 2008 [53]	LPN	Intraoperative C-Arm CT, CT	Introduction and evaluation of a navigation system for kidney interventions	Use of custom-designed navigation aids; intraoperative CT is used for registration with preoperative CT images	In vitro: simulated data; in vivo: 3 porcine kidneys
Benincasa et al. 2008 [72]	LPN, OPN	Laparoscopic video, CT	Optimization of surface-based registration	Iterative closest point algorithm; determination of required surface fraction	Laboratory study on phantom
Ong et al. 2016 [73]	PN, RN	Laparoscopic video	Surface extraction for intraoperative surface-based registration	Texture-mapping of a surface obtained by a conoscope using a laparoscopic camera	Ex vivo: phantom, porcine and human kidneys
Estepar et al. 2009 [74]	LPN	IOUS, CT	Improvement of registration for small shifts from the initial registration.	Phase correlation technique	Laboratory study on phantom
Edgcumbe et al. 2015 [75]	LPN	Laparoscopic video stream	Surface reconstruction for surface-based registration	Use of miniaturized projector for intraoperative surface reconstruction and AR visualization	Ex vivo: porcine kidneys; in vivo: porcine model
Kingma et al. 2011 [76]	PN, RN	IOUS, CT	Optimization of the initialization of feature-based registration	Fiducial pad for automatic initial rigid registration	Laboratory study on phantom
Schneider et al. 2016 [77]	LPN, RAPN	IOUS, CT	Registration of IOUS with CT, integration into RAPN	Custom-designed intraoperative "pick-up" ultrasound transducer, tracking of probe	Laboratory study on phantom
Puerto-Souza et al. 2011 [78]	LPN	Laparoscopic video, CT	Introduction of feature-matching algorithm	Adaptive multi-affine algorithm based on clustering	Retrospective study: 50 image-pairs from 3 LPN
Puerto-Souza et al. 2013 [79]	LPN	Laparoscopic video, CT	Optimization of feature-matching regarding speed, accuracy, and robustness	Hierarchical multi-affine algorithm	Retrospective study: 100 images from 6 LPN
Puerto-Souza et al. 2014 [80]	LPN	Laparoscopic video, CT	Optimization of feature-matching regarding long-term AR	Sliding-window weighted least-squares criterion that allows to recover the position of anchor points	Retrospective study: 2 video sequences of LPN
Yip et al. 2012 [81]	RAPN	Laparoscopic video stream	Feature-based tracking and registration update for stereo laparoscopy	Calculation of rigid transformation based on surface feature assuming an initial registration	In vitro: data from in vivo porcine model, patient data from RAPN
Wild et al. 2016 [82]	LPN, LRN	Laparoscopic video, CT	Improvement of intraoperative registration	Use of metabolizable fluorescent markers as fiducials for inside-out tracking	Ex vivo: porcine liver and kidney
Glisson et al. 2011 [83]	OPN	Laparoscopic video, CT	Improvement of intraoperative re-registration	Use of "virtual fiducials" for point-based intraoperative re-registration	In vivo: three OPN cases

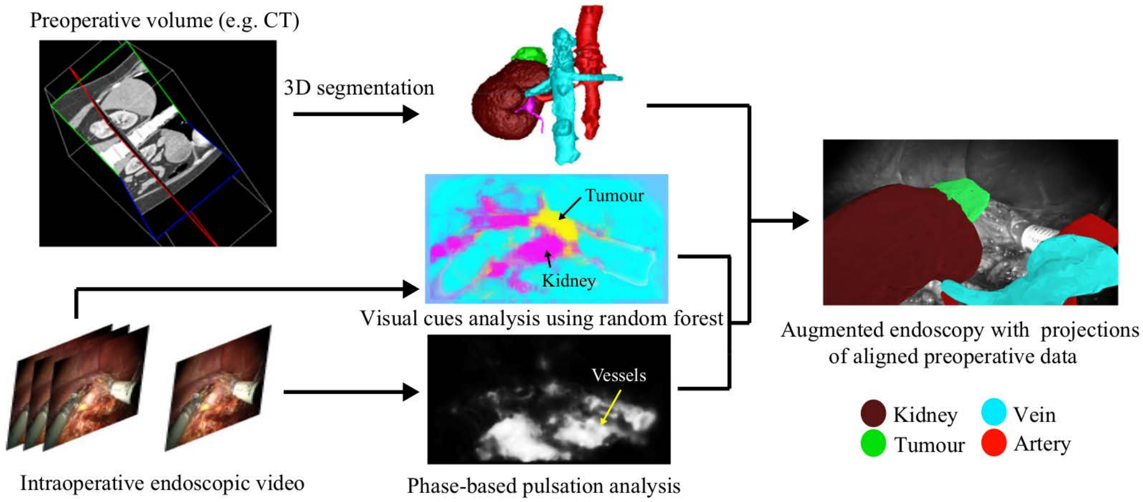

Fig. 8. Illustration of method for image guidance by augmentation of endoscopic video with kidney, tumor and vessel boundaries. Figure adapted based on [68].

indicating a possible AR application of the projector.

Kingma et al. [76] address the problem of required proper (manual) initialization of many feature-based methods with regard to registration of preoperative CT images with laparoscopic IOUS. They design a pad based on polyvinyl chloride with integrated fiducials that is attached to the patient during preoperative scanning and intervention, which can be used for automatic initial rigid registration of the CT and the IOUS image. Clinical evaluation on three patients undergoing nephrectomy reveals a TRE up to 18.72 mm (3.3 mm in a phantom study), which is considered as sufficient for initialization of feature-based algorithms.

Also with regard to registration of preoperative CT images with laparoscopic IOUS, Schneider et al. [77] introduce an intraoperative "pick-up" ultrasound transducer, which can be used for RAPN without requiring a dedicated port or robotic tool change. For intraoperative registration, the transducer is tracked by using robotic kinematics, an electromagnetic (EM) tracking system, or optical tracking with the stereo endoscope. Tracking by robotic kinematics is associated with the smallest average TRE on a ultrasound vessel phantom.

Puerto-Souza et al. [78], [79], [80] developed a method for robust and long-term AR overlay of 3D models generated from CT data on monocular endoscopic video (with or without camera calibration) based on feature matching algorithms. Related to high computational effort of their initial adaptive multi-affine algorithm [78], a computationally more efficient and robust hierarchical multi-affine algorithm (HMA) [79] is proposed and evaluated. HMA hierarchically clusters initial appearance-based feature matches and iteratively removes incorrect matches by estimating affine transformations for each cluster. This approach, being evaluated by comparison of performance with other algorithms [78], [85], [86] on datasets from laboratory and LPN videos, allows for fast and robust feature matching, also after temporally lost feature matches due to visual occlusion. The algorithm is applied in [80] for the implementation of a tracking recovery phase for cases when the algorithm loses tracked features. Based on the feature tracking, anchor points for the projection of the 3D model on the endoscopic video are updated and the augmentation is updated for each subsequent video frame. Comparison of the performance of the two projection methods, with or without incorporation of camera calibration, on videos from LPN to another algorithm yielded higher accuracy for the proposed algorithms and the most accurate overlay for the method, including camera calibration parameters.

Yip et al. [81] use a combination of a modified version of the CenSuRE (Center Surround Extremas for Realtime Feature Detection and Matching) feature detector [87] and the binary robust independent elementary feature (BRIEF) descriptor [88] for tracking of tissue in stereo endoscope video. In contrast to [80], effects of instrument occlusions or shading are not handled by their method.

Because of the difficulties associated with the use of implanted fiducials for intraoperative registration, Wild et al. [82] suggest the application of metabolizable fluorescent markers for registration of a preoperative 3D model with the endoscopic video in laparoscopic procedures. A comparison of this method with needle-shaped implanted fiducials on porcine kidneys revealed an equal number of successfully processed frames (defined as frames where all markers were detected and the fiducial visualization error (FVE) was smaller than 25 pixels) for both approaches. Furthermore, the robustness of the proposed method was assessed on porcine livers where blood, tissue or smoke (partially) occluded the fiducials. In all three set-ups, the use of fluorescent markers resulted in a considerably better detection of the fiducials.

A similar approach with respect to the extent of invasiveness of the use of fiducials is presented by Glisson et al. [83] for OPN. After an initial surface-based registration of the kidney surface obtained from laser range scanning with a preoperative model, dots ("virtual fiducials") are placed on the kidney and used for subsequent point-based re-registration during the procedure.

A comprehensive review and evaluation of different surface reconstruction methods for laparoscopic procedures can be found in [89].

A major difficulty encountered with registration is the permanent deformation of organs and instruments, resulting in insufficiently accurate registration. Deformation models addressing various origins of deformation have been proposed to enable automatic and accurate registration when tissue or organ deformation is present (see Table V). Two models consider deformation resulting from renal clamping and incision [56], [90]. Kidney tissue is assumed to behave as linear elastic homogenous isotropic or anisotropic tissue. The models are evaluated on porcine kidneys by using fiducials to calculate the differences between fiducial displacement predicted by the model and the actual displacement derived from CT images. The average TRE is 3.3 mm in the isotropic and 3.0 mm in the anisotropic case [56].

Tissue deformation occurring due to external pressure load, e.g. resulting from insufflation during laparoscopic interventions, is addressed by Figueroa-Garcia et al. [91]. Their model is used to preoperatively estimate the organ shape and tumor position for RAPN or LPN procedures. An FEM with linear elastic corotational kinematic description is applied to a 3D volumetric mesh (generated from semi-automatically segmented kidney parenchyma and tumor) to model the deformation. Evaluation with the same fiducial-based approach as in [56], [90] yields an improvement of 29% of the registration error using the deformation model over the solely rigid transformation. Assessment of the ex vivo kidney deformation occurring under external pressure load results in an average change of 2.17 mm of the relative distance from the tumor centroid to the kidney surface.

Another FEM model for simulation of deformation is proposed by Nishiyama et al. [92]. In contrast to [91], a non-linear model is presented. Hyper-elastic material properties are incorporated into the FEM stiffness matrix by decomposition of the stress-strain relation into several functions of strain. A comparison of the proposed method with a commercially available non-linear FEM solver yielded a similar calculated deformation for a uniaxial tensile test. Besides, the simulation of the deformation was significantly faster with the new method.

A method developed by Hostettler et al. [93] relies on tracking the patient skin surface in real-time and modeling diaphragm motion and its influence on the kidney movement and deformation. Two preoperative CT scans in inspired and expired position, respectively, are used to incorporate the individual patient anatomy for extraction of the organ meshes and modeling the diaphragm motion during breathing. The model is evaluated by acquiring a third CT scan in expiration position for comparison of the real positions with the simulated positions of the internal organs. In this evaluation case, the skin is extracted from CT data. From both the predicted and the actual organ positions, the extracted meshes were used to calculate the average distance between the gravity center of each triangle position in the simulated and the surface mesh. Computed errors for the kidney models were lower than 2 mm.

D. Aspects of Clinical Evaluation

To review the actual state of VR/AR systems in clinical practice, this section presents studies in clinical settings with respect to the integration into the clinical workflow and their influence on patient outcomes (see Table VI).

In general, VR/AR assistance is described as helpful [38], [40], [49], [52], [57], [59]. Concerning PN interventions with complex vascular structures, such systems can improve the identification of vessels by providing preoperative planning support (VR) or intraoparative guidance (AR) [39], [41], [52], [58], [59], [95]. With respect to PCNL procedures, AR systems are primarily used for trajectory guidance and are considered as helpful for assistance in reaching the target while avoiding risk structures [45], [48], [49].

In most of the studies, the described systems are evaluated qualitatively with respect to patient outcome. Only one research group performs a retrospective quantitative evaluation of patient outcome and procedure parameters for LPN with and without AR assistance [41]. Outcomes of LPN procedures performed in 22 patients with assistance of a 3D model for preoperative planning and intraoperative manual image fusion are compared to those of 14 LPN procedures without VR/AR assistance. Statistical evaluation reveals a significantly reduced mean operation time (159.0 vs. 193.2 min) and mean estimated blood loss (148.1 vs. 176.1 ml). No significant differences are found for mean segmental renal artery clamping time, postoperative hospital stay duration and several renal function parameters.

Another study where performance is evaluated quantitatively deals with the intraoperative use of "panoramic views" [94]. It can be shown that novices being supported by panoramic views from the very beginning of performing LRN procedures perform significantly better with respect to blood loss and operation time than the novices without assistance.

To enable an enhanced outcome for the patient using VR/AR systems, it is important to consider the clinical user's perspective. With respect to the intraoperative workflow, no modification occurs in the case of purely preoperative VR assistance for precise planning [52]. Besides support in preoperative planning, VR models are displayed intraoperatively to enhance the surgeon's 3D orientation and visualize important risk or target structures [38], [39], [49], [58], [59]. Manipulation of the 3D model allows the surgeon to adapt the model's orientation to the actual operative view, thus supporting guidance, but also increases the amount of human-computer interaction. The standard clinical workflow is altered most in cases where images are intraoperatively fused in a manual way. In two of the reported cases, an additional surgical technician or surgical assistant performs the image fusion, so that the surgeon is not exposed to additional burden and the surgical process is not slowed down [33], [41]. A median manual fusion time of six minutes is reported in [33]. In the clinical application of two systems, the surgeon is actively involved in the augmentation procedure. For an accurate surface-based registration, the kidney surface is manually screened with a tracked robotic instrument in [56]. No information about the time required for the registration process is reported.

TABLE V
REGISTRATION TECHNIQUES FOR VR/AR SYSTEMS USING APPROACHES BASED ON DEFORMATION MODELS ADDRESSING RADICAL NEPHRECTOMY (RN) AND PARTIAL NEPHRECTOMY (PN), I.E. LAPAROSCOPIC PARTIAL NEPHRECTOMY (LPN) AND OPEN PARTIAL NEPHRECTOMY (OPN). IF NOT STATED OTHERWISE, CT REFERS TO PREOPERATIVE CT.

	Procedure	Modalities	Objective	Method	Evaluation
Ong et al. 2008 [90]	LPN	Tracking data, CT	Introduction of a kidney deformation model; calculation of non-rigid deformation	Biot's consolidation model	Ex vivo: 2 porcine kidneys
Altamar et al. 2011 [56]	RAPN	Tracking data, CT	Incorporation of a kidney deformation model into navigation system	Isotropic and anisotropic linear elastic mathematical model	Ex vivo: 6 porcine kidneys
Figueroa-Garcia et al. 2014 [91]	RAPN LPN	CT, CT	Introduction of a kidney deformation model	Finte element mesh with linear elastic corotational kinematic description	Laboratory study: 5 ex vivo lamb kidneys with fiducials
Nishiyama et al. 2015 [92]	PN	*not specified*	Introduction of a non-linear FEM deformation model	Hyper-elastic material properties incorporated in FEM stiffness matrix	Labaratory study: kidney model
Hostetter et al. 2010 [93]		Tracking data, CT	Introduction of a kidney deformation model to handle free breathing	Real time tracking of patient skin and modeling of diaphragmatic boundary	Retrospective study: CT data from 2 patients

In [55], both the 3D model reconstruction and the fusion with the endoscopic video are performed intraoperatively. The maximum time for model creation and fusion is stated as seven minutes with a total surgery duration of 235 minutes for this case. However, the accuracy of the fused image is limited.

E. Aspect of Human Factors

Studies addressing the user perspective were identified in the literature search. A very important aspect to be considered is the effect of AR on the ability of the surgeon to perceive important structures. One study addresses this aspect by investigating the impact of cognitive load and AR image guidance on inattention blindness during the surgery [96]. Segments of videos from RAPN procedures are presented to three different groups of surgeons, who subsequently answer a questionnaire to assess unprompted and prompted attention. During the video presentation, either a wireframe AR overlay, a solid overlay, or no overlay at all is presented to each of the three respective groups. These groups are further subdivided by subjecting one half of them to additional cognitive load, resulting in six groups in total. The results show a significant impact of cognitive load on inattention for objects outside the image focus, but no significant effect of AR overlay. Generally, a relatively high level of inattention for items outside the focus is recognized. Another study assesses the actual use of pre- and intraoperative image modalities in robotic urological interventions (RAPN, robot-assisted laparoscopic prostatectomy and/or robotic cystectomy) with a questionnaire answered by 117 independently practicing robotic surgeons [97]. In total, 87% of the questioned surgeons envisaged a role for AR with the highest amount of agreement among surgeons performing RAPN. From these surgeons, asked in which parts of the operation they would see AR as an assistance, the highest amount of consent (74 %) was found for identification of tumor location. Concerning intraoperative imaging, a majority of surgeons performing RAPN use IOUS, thus, indicating that this image modality could be used for AR in a realistic clinical setting.

With regard to the user impact on AR outcome, Hughes-Hallett et al. [98] evaluate the effect of manual segmentation on the segmentation result of renal tumors. A ground truth for comparison is calculated by applying the STAPLE (simultaneous truth and performance level estimation) algorithm [99]. The results show significant differences in segmentation between different raters and also between groups of raters with different levels of clinical and segmentation experience. Participants with pathology-specific imaging experience were found to segment the tumor in a more radical way without an increase in the amount of tumor left unsegmented.

IV. DISCUSSION

Renal interventions pose several challenges, such as safe tumor resection during LPN or avoiding risk structures during PCNL. For support in these interventions, different computer-assisted systems have been developed to improve patient outcome. Except two systems [39], [83], all identified systems deal with minimally invasive interventions. These findings emphasize the important role of assistance systems in minimally invasive interventions, such as LPN. LPN has gained increasing interest due to a decreased operative blood loss and shorter hospital stay, but is at the same time related to difficulties resulting from a reduced haptic feedback and a limited field of view [13], [14], [54], [100]. VR/AR systems address these limitations by providing additional information pre- and intraoperatively. More than half of the identified systems for PN (11/21) deal with robotic-assisted procedures, thus, demonstrating the importance of this topic. Furthermore, although the search strategy included computer assistance for RCC resection and renal stone treatments, most of the described systems deal with PN procedures. Different aspects might explain this finding. For renal stone treatment, minimally invasive procedures have already been well established as a clinical standard. The initial puncture of the renal calyx is the only step with potential benefit of AR support. LPN and RAPN on the other hand are complex surgical interventions, where VR/AR systems can support different phases of the

TABLE VI
VR/AR SYSTEMS THAT ARE **EVALUATED IN A CLINICAL SETTING**.

	Procedure	Approach	Number of Patients	Results
Ukimura et al. 2008 [35]	LPN	Augmentation of endoscopic view by virtual tumor margins	1	Accuracy in superimposition sufficient for precise 3D orientation
Teber et al. 2009 [54]	LPN	Augmentation of endoscopic video by 3D model from preoperative CT	10	Accuracy in superimposition sufficient for precise 3D orientation, AR guidance especially helpful in cases with vessels hidden in parenchymal fat
Chen et al. 2014 [33]	LPN	Augmentation of endoscopic view by 3D model from preoperative CT	15	Successful reconstruction of 3D models, median time to obtain fused images 6 min
Wang et al. 2015 [41]	LPN	Intraoperative manual fusion of 3D model with endoscopic video	35	Significantly reduced operation time and estimated blood loss when using AR system
Isotani et al. 2015 [42]	LPN	Preoperative simulation of PN and intraoperative display of 3D model below endoscopic video	20	Quantitative predictors from simulations in accordance with post-operative outcomes
Komai et al. 2014 [39]	LPN, OPN	3D model for planning and intraoperative guidance	22 (LPN), 4 (OPN)	Model consistent with intraoperative findings in all cases, supports “clampless” PN
Glisson et al. 2011 [83]	OPN	Use of virtual “fiducials” for point-based intraoperative re-registration	3	Point-based registration by using dots spread on kidney surface can be used for deformation tracking
Makiyama et al. 2015 [52]	LPN, LRN	Simulator based on individual patient CT data for “rehearsal” surgeries	13	Simulator especially useful in two cases with complex anatomical relations; high content validity score
Nakamura et al. 2010 [55]	LPN, LRN	Augmentation of endoscopic video by intraoperatively reconstructed 3D model	2 (LPN), 3 (LRN)	Relatively fast and easy reconstruction of model and fusion with endoscopic video, no high accuracy
Naya et al. 2009 [94]	LRN	Display of panoramic views obtained from endoscopic video during surgery	40	Surgeries conducted by novices using panoramic views related to significantly shorter operating time and blood loss
Ukimura et al. 2012 [40]	LPN, RAPN	3D model for planning and intraoperative guidance	4	3D model helpful for identification of vessels for “Zero ischemia” PN
Altamar et al. 2011 [56]	RAPN	Registration of endoscopic video with preoperative CT	*Not stated*	Accuracy considered as “qualitatively good”
Furukawa et al. 2014 [38]	RAPN	3D model displayed below endoscopic video on robotic console	17	System considered as helpful to obtain detailed spatial information and to identify targeted arterial branches
Hughes-Hallett et al. 2014 [59]	RAPN	3D model for planning and display below endoscopic video on robotic console	5	System considered as helpful, especially in case with complex renal vascular anatomy
Pratt et al. 2015 [57]	RAPN	Augmentation of endoscopic video with laparoscopic IOUS image	1	AR overlay considered by surgeon as efficacious
Lasser et al. 2012 [58]	RAPN	3D model for planning and display below endoscopic video on robotic console	10	Precise planning and 3D model display considered as especially helpful for complex vascular anatomy
Rassweiler et al. 2012 [48]	PCNL	Augmentation of tablet camera view by 3D planning model from preoperative CT	2	Demonstration of clinical feasibility of system, used for determination of puncture site
Li et al. 2013 [49]	PCNL	3D model for detailed preoperative planning and intraoperative guidance	15	Model considered by surgeon as helpful
Mozer et al. 2007 [45]	PCNL	Augmentation of IOUS image by preoperative CT images for navigation	1	Needle tract on fluoroscopy image corresponds to the one targeted by surgeon

procedure. Independent of the surgery itself, current urological research shows a clear trend towards the oncological fields, thus further explaining the comparatively high amount of literature dealing with RCC treatment.

Concerning the clinical evaluation of the presented systems, only 44% (20/45) of the identified approaches have already been applied in clinical practice. Nine were evaluated on ten or more patients, with the highest amounts of patients for evaluation being 35 [41] and 40 [94]. Compared to other clinical trials, this amount is quite low [8], [101] and limits the option to provide evidence of improved outcomes by the use of VR/AR systems. Only one study statistically evaluating the impact of AR systems on different surgical parameters indicates that AR support yields indeed an improved outcome [41]. However, the system is used intraoperatively for augmentation as well as preoperatively for precise planning including virtual resections, so that the additional value of AR over VR remains unclear. To support a transformation of VR/AR approaches from research into clinical practice, more quantitative evaluation of outcome - also with respect to costs related to the use of the system - will be necessary. Because of high regulatory hurdles and hence financial challenges for the evaluation and implementation of new technologies in clinical settings, also the role of cooperations with manufactures is gaining of importance [102].

Several difficulties are related to VR/AR support: The generation of 3D models used for simulation purposes can be very time-consuming [51]. Once the 3D model is created, an AR overlay needs to take organ motion into account. Methods to deal with this, such as manual image registration, require additional resources and can alter the intraoperative workflow [33], [41], [55]. This aspect might explain why the implementation of AR systems in urology is proceeding more slowly than in other fields, e.g., in neurosurgery, where computer-assisted navigation systems are used in clinical routine and bone structures can be used for rigid registration [103], [104]. Furthermore, most of the approaches to incorporate deformation address only one source of motion [91], [93], [105], so that models incorporating several reasons for deformation would be needed. Another problem influencing the ability to represent the patient's anatomy correctly for VR/AR support is intra- and inter-user variability for manual segmentation [98], which is applied in several cases [58], [59]. The effect of segmentation variability on augmentation of tumor margins for PN procedures could possibly be addressed by the approach of Amir-Khalili et al. [32], allowing for automatic segmentation and encoding of probabilities of the segmentation result. Manual segmentation is also often used as ground truth for evaluation of (semi-)automatic segmentation or registration approaches, thus limiting the validity of the results [69], [79].

With respect to user interaction, surgeons generally seem to handle manipulation of 3D models relatively easily [55]. Nevertheless, some methods were demonstrated to be more intuitive than others, such as the manipulation with a tablet computer rather than a 3D mouse [59]. This aspect is also related to the user's (surgeon's) individual experiences and thus emphasizes the need to consider the intuitiveness of interaction when designing VR/AR systems.

Another aspect which is important for the effectiveness of AR support in clinical practice is inattention blindness resulting from the AR overlay. Whereas Hughes-Hallett et al. [96] did not find a significant increase in it when presenting an AR overlay for RAPN procedures, Dixon et al. [106] demonstrated the opposite in the field of otolaryngology. Although the studies differ in their design (in [106] an endoscopic task is performed on a cadaveric specimen, whereas RAPN videos are presented to the participants in [96]), the findings demonstrate that the influence of AR on inattention blindness is not unambiguous and further investigations – also under clinical conditions – are required. The problem of AR overlay distracting the view on the operation field is also reported in [32], where different possible AR views are compared and the ones presenting several contours are considered as obstructing the kidney. Hence, not only the influence of the AR overlay itself, but also of its realization needs to be considered. Furthermore, the cognitive load which could be related to the use of the AR system should be minimized [96].

Also important regarding different VR/AR systems is the extent to which the clinical workflow is altered by the use of the assistance systems. As presented, the amount of change in the intraoperative process varies depending on the human factors which are involved. Moreover, for results from evaluations of AR approaches, such as those suggesting not to move the surgical instrument during video acquisition [36], the impact of this instruction should be carefully weighed against the added value from the system. Besides the effect on the intraoperative procedure, the additional effort on preoperative planning also needs to be taken into account. The time required for obtaining 3D planning models has a range from a few minutes [43] to several hours [51]. One option to reduce the planning effort, which is already applied in clinical routine, consists in outsourcing the reconstruction of the 3D model from imaging data [58].

This review focused, for the treatment of RCC, on surgical (minimally invasive) resection. It should be noted that even less-invasive treatment options exist. They include high intensity focused ultrasound (HIFU), RFA, and cryoablation. Whereas RN or PN are recommended as standard treatment options for RCC, ablation techniques are considered as optional alternatives for older patients or patients with substantial comorbidities. HIFU is currently seen as an experimental approach [5], [107]. As the majority of renal tumors are treated by resection of the tumor and hence most of the VR/AR systems are designed for assistance in those intervention, this review covers these systems. After more clinical experience with ablation techniques, a future review could also include systems for those interventions.

With regard to the technical evaluation of the presented approaches, a comparison between different methods is difficult due to various metrics that were selected for quantitative assessment. Whereas for the registration techniques evaluation was in several cases based on the TRE, different metrics such as the dice similarity coefficient or sensitivity and specificity were presented in case of segmentation methods [56], [65], [66], [67], [72], [76]. Fully developed systems were mainly evaluated in a solely qualitative manner (see Tab. I and II).

To conclude the discussion, following challenges should be addressed in the future:

- Reduction of additional workload for the use of the assistance systems, e.g., by taking human factor issues and advanced methods for human-computer interaction into account.
- Clinical studies with an increased number of participants to demonstrate (quantitative) evidence for an improved outcome resulting from VR/AR systems. Also, cost-effectiveness needs to be evaluated.
- Incorporation of organ movement and deformation by real-time tracking and/or deformation models taking more than one source of motion into account.
- Intraoperative visualization of uncertainty, in particular regarding errors in segmentation, registration, and tracking.

As mentioned above, more than half of the AR systems were applied in RAPN procedures. Whereas most of them could also be applied in non-robotic-assisted endoscopic procedures, some of them rely on the position information obtained from the robotic arm. While different types of imaging systems are widely available as standard equipment in hospitals, robotic systems are encountered less frequently. In order to enable the broad use of AR systems, it will therefore be important to also develop assistance systems that can be readily used in simple endoscopic setups.

V. Conclusion

This literature review shows the extent to which VR/AR support is already used in clinical practice. Furthermore, there is a desire for an increased use of AR systems in urology [97]. VR/AR has the potential to improve the safety and outcome of renal interventions in the future. Although results from large clinical studies are not yet reported in the literature, many advances in the last ten years have led to sophisticated systems. Further interdisciplinary research is required to cope with current limitations of VR/AR assistance in clinical environments.

Acknowledgment

The work of this paper was partly funded by the German Research Foundation (DFG) under grant number HA 7819/1-1.

Conflict of Interest

The authors declare that they have no conflict of interest.

Ethical Standard

This article does not contain any studies with human participants or animals performed by any of the authors.

References

[1] C. D. Scales, A. C. Smith, J. M. Hanley, and C. S. Saigal, "Prevalence of kidney stones in the United States," *Eur. Urol.*, vol. 62, no. 1, pp. 160–165, Jul 2012.

[2] A. Ramello, C. Vitale, and M. Marangella, "Epidemiology of nephrolithiasis," *J. Nephrol.*, vol. 13 Suppl 3, pp. 45–50, Nov-Dec 2000.

[3] E. Jonasch, J. Gao, and W. K. Rathmell, "Renal cell carcinoma," *BMJ*, vol. 349, p. g4797, Nov 2014.

[4] R. L. Siegel, K. D. Miller, and A. Jemal, "Cancer statistics, 2015," *CA Cancer J Clin*, vol. 65, no. 1, pp. 5–29, Jan 2015.

[5] *Guideline for Management of the Clinical Stage 1 Renal Mass*, American Urological Association Education and Research, Inc, Linthicum, USA, 2009.

[6] I. S. Gill, M. Aron, D. A. Gervais, and M. A. Jewett, "Clinical practice. Small renal mass," *N. Engl. J. Med.*, vol. 362, no. 7, pp. 624–634, Feb 2010.

[7] T. C. Lai, W. K. Ma, and M. K. Yiu, "Partial nephrectomy for T1 renal cancer can achieve an equivalent oncological outcome to radical nephrectomy with better renal preservation: the way to go," *Hong Kong Med J*, vol. 22, no. 1, pp. 39–45, Feb 2016.

[8] H. J. Tan, E. C. Norton, Z. Ye, K. S. Hafez, J. L. Gore, and D. C. Miller, "Long-term survival following partial vs radical nephrectomy among older patients with early-stage kidney cancer," *JAMA*, vol. 307, no. 15, pp. 1629–1635, Apr 2012.

[9] D. A. Gervais, F. J. McGovern, R. S. Arellano, W. S. McDougal, and P. R. Mueller, "Radiofrequency Ablation of Renal Cell Carcinoma: Part 1, Indications, Results, and Role in Patient Management over a 6-Year Period and Ablation of 100 Tumors," *AJR Am J Roentgenol*, vol. 185, no. 1, pp. 64–71, Jul 2005.

[10] B. Ljungberg, K. Bensalah, S. Canfield, S. Dabestani, F. Hofmann, M. Hora, M. A. Kuczyk, T. Lam, L. Marconi, A. S. Merseburger, P. Mulders, T. Powles, M. Staehler, A. Volpe, and A. Bex, "EAU guidelines on renal cell carcinoma: 2014 update," *Eur. Urol.*, vol. 67, no. 5, pp. 913–924, May 2015.

[11] J. S. Ellison, J. S. Montgomery, J. S. Wolf, K. S. Hafez, D. C. Miller, and A. Z. Weizer, "A matched comparison of perioperative outcomes of a single laparoscopic surgeon versus a multisurgeon robot-assisted cohort for partial nephrectomy," *J. Urol.*, vol. 188, no. 1, pp. 45–50, Jul 2012.

[12] R. P. Wijn, M. C. Persoon, B. M. Schout, E. J. Martens, A. J. Scherpbier, and A. J. Hendrikx, "Virtual reality laparoscopic nephrectomy simulator is lacking in construct validity," *J. Endourol.*, vol. 24, no. 1, pp. 117–122, Jan 2010.

[13] A. Al-Aown, P. Kallidonis, S. Kontogiannis, I. Kyriayis, V. Panagopoulos, J. U. Stolzenburg, and E. Liatsikos, "Laparoscopic radical and partial nephrectomy: The clinical efficacy and acceptance of the techniques," *Urol Ann*, vol. 6, no. 2, pp. 101–106, Apr 2014.

[14] I. S. Gill, L. R. Kavoussi, B. R. Lane, M. L. Blute, D. Babineau, J. R. Colombo, I. Frank, S. Permpongkosol, C. J. Weight, J. H. Kaouk, M. W. Kattan, and A. C. Novick, "Comparison of 1,800 laparoscopic and open partial nephrectomies for single renal tumors," *J. Urol.*, vol. 178, no. 1, pp. 41–46, Jul 2007.

[15] L. M. Su, B. P. Vagvolgyi, R. Agarwal, C. E. Reiley, R. H. Taylor, and G. D. Hager, "Augmented reality during robot-assisted laparoscopic partial nephrectomy: toward real-time 3D-CT to stereoscopic video registration," *Urology*, vol. 73, no. 4, pp. 896–900, Apr 2009.

[16] Y. Funahashi, R. Hattori, T. Yamamoto, O. Kamihira, K. Kato, and M. Gotoh, "Ischemic renal damage after nephron-sparing surgery in patients with normal contralateral kidney," *Eur. Urol.*, vol. 55, no. 1, pp. 209–215, Jan 2009.

[17] S. Mishra, A. Kurien, A. Ganpule, V. Muthu, R. Sabnis, and M. Desai, "Percutaneous renal access training: content validation comparison between a live porcine and a virtual reality (VR) simulation model," *BJU International*, vol. 106, no. 11, pp. 1753–1756, Oct 2010.

[18] J. Stern, I. S. Zeltser, and M. S. Pearle, "Percutaneous renal access simulators," *J. Endourol.*, vol. 21, no. 3, pp. 270–273, Mar 2007.

[19] "Encyclopedia britannica online, Virtual Reality (VR)," http://www.britannica.com/technology/virtual-reality, 2015, accessed: November 2015.

[20] R. T. Azuma, "A survey of augmented reality," *Presence: Teleoperators and Virtual Environments*, vol. 6, no. 4, pp. 355–385, Aug. 1997.

[21] B. Preim and C. P. Botha, *Visual Computing for Medicine: Theory, Algorithms, and Applications*, 2nd ed. San Francisco, CA, USA: Morgan Kaufmann Publishers Inc., 2013.

[22] S. Micali, G. Pini, D. Teber, M. C. Sighinolfi, S. De Stefani, G. Bianchi, and J. Rassweiler, "New trends in minimally invasive urological surgery: what is beyond the robot?" *World J Urol*, vol. 31, no. 3, pp. 505–513, Jun 2013.

[23] A. Pervez, K. Ahmed, S. Thompson, O. Elhage, M. S. Khan, and P. Dasgupta, "Image guided robotic surgery: current evidence for effectiveness in urology," *Arch Ital Urol Androl*, vol. 86, no. 4, pp. 245–248, Dec 2014.

[24] S. D. Herrell, R. L. Galloway, and L. M. Su, "Image-guided robotic surgery: update on research and potential applications in urologic surgery," *Curr Opin Urol*, vol. 22, no. 1, pp. 47–54, Jan 2012.

[25] N. Najmaei, K. Mostafavi, S. Shahbazi, and M. Azizian, "Image-guided techniques in renal and hepatic interventions," *Int J Med Robot*, vol. 9, no. 4, pp. 379–395, Dec 2013.

[26] J. Rassweiler, M. C. Rassweiler, M. Muller, H. Kenngott, H. P. Meinzer, D. Teber, E. Lima, B. Petrut, J. Klein, A. S. Gozen, M. Ritter, and M. S. Michel, "Surgical navigation in urology: European perspective," *Curr Opin Urol*, vol. 24, no. 1, pp. 81–97, Jan 2014.

[27] M. Nakamoto, O. Ukimura, K. Faber, and I. S. Gill, "Current progress on augmented reality visualization in endoscopic surgery," *Curr Opin Urol*, vol. 22, no. 2, pp. 121–126, Mar 2012.

[28] S. Nicolau, L. Soler, D. Mutter, and J. Marescaux, "Augmented reality in laparoscopic surgical oncology," *Surg Oncol*, vol. 20, no. 3, pp. 189–201, Sep 2011.

[29] A. Hughes-Hallett, E. K. Mayer, H. J. Marcus, T. P. Cundy, P. J. Pratt, A. W. Darzi, and J. A. Vale, "Augmented reality partial nephrectomy: examining the current status and future perspectives," *Urology*, vol. 83, no. 2, pp. 266–273, Feb 2014.

[30] A. Moglia, V. Ferrari, L. Morelli, M. Ferrari, F. Mosca, and A. Cuschieri, "A Systematic Review of Virtual Reality Simulators for Robot-assisted Surgery," *Eur. Urol.*, vol. 69, no. 6, pp. 1065–1080, Jun 2016.

[31] D. Moher, A. Liberati, J. Tetzlaff, D. G. Altman, D. Altman, G. Antes, D. Atkins, V. Barbour, N. Barrowman, J. A. Berlin, J. Clark, M. Clarke, D. Cook, R. D'Amico, J. J. Deeks, P. J. Devereaux, K. Dickersin, M. Egger, E. Ernst, P. C. G?tzsche, J. Grimshaw, G. Guyatt, J. Higgins, J. P. Ioannidis, J. Kleijnen, T. Lang, A. Liberati, N. Magrini, D. McNamee, L. Moja, D. Moher, C. Mulrow, M. Napoli, A. Oxman, B. Pham, D. Rennie, M. Sampson, K. F. Schulz, P. G. Shekelle, J. Tetzlaff, D. Tovey, and P. Tugwell, "Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement," *Int J Surg*, vol. 8, no. 5, pp. 336–341, May 2010.

[32] A. Amir-Khalili, M. S. Nosrati, J.-M. Peyrat, G. Hamarneh, and R. Abugharbieh, "Uncertainty-encoded augmented reality for robot-assisted partial nephrectomy: A phantom study," *Augmented Reality*

Environments for Medical Imaging and Computer-Assisted Interventions, pp. 182–191, 2013.

[33] Y. Chen, H. Li, D. Wu, K. Bi, and C. Liu, "Surgical planning and manual image fusion based on 3D model facilitate laparoscopic partial nephrectomy for intrarenal tumors," *World J Urol*, vol. 32, no. 6, pp. 1493–1499, Dec 2014.

[34] C. L. Cheung, C. Wedlake, J. Moore, S. E. Pautler, and T. M. Peters, "Fused video and ultrasound images for minimally invasive partial nephrectomy: a phantom study," *Med Image Comput Comput Assist Interv*, vol. 13, no. Pt 3, pp. 408–415, 2010.

[35] O. Ukimura and I. S. Gill, "Imaging-assisted endoscopic surgery: Cleveland Clinic experience," *J. Endourol.*, vol. 22, no. 4, pp. 803–810, Apr 2008.

[36] A. Amir-Khalili, J. M. Peyrat, J. Abinahed, O. Al-Alao, A. Al-Ansari, G. Hamarneh, and R. Abugharbieh, "Auto localization and segmentation of occluded vessels in robot-assisted partial nephrectomy," *Med Image Comput Comput Assist Interv*, vol. 17, no. Pt 1, pp. 407–414, 2014.

[37] A. Amir-Khalili, G. Hamarneh, J. M. Peyrat, J. Abinahed, O. Al-Alao, A. Al-Ansari, and R. Abugharbieh, "Automatic segmentation of occluded vasculature via pulsatile motion analysis in endoscopic robot-assisted partial nephrectomy video," *Med Image Anal*, vol. 25, no. 1, pp. 103–110, Oct 2015.

[38] J. Furukawa, H. Miyake, K. Tanaka, M. Sugimoto, and M. Fujisawa, "Console-integrated real-time three-dimensional image overlay navigation for robot-assisted partial nephrectomy with selective arterial clamping: early single-centre experience with 17 cases," *Int J Med Robot*, vol. 10, no. 4, pp. 385–390, Dec 2014.

[39] Y. Komai, Y. Sakai, N. Gotohda, T. Kobayashi, S. Kawakami, and N. Saito, "A novel 3-dimensional image analysis system for case-specific kidney anatomy and surgical simulation to facilitate clampless partial nephrectomy," *Urology*, vol. 83, no. 2, pp. 500–506, Feb 2014.

[40] O. Ukimura, M. Nakamoto, and I. S. Gill, "Three-dimensional reconstruction of renovascular-tumor anatomy to facilitate zero-ischemia partial nephrectomy," *Eur. Urol.*, vol. 61, no. 1, pp. 211–217, Jan 2012.

[41] D. Wang, B. Zhang, X. Yuan, X. Zhang, and C. Liu, "Preoperative planning and real-time assisted navigation by three-dimensional individual digital model in partial nephrectomy with three-dimensional laparoscopic system," *Int J Comput Assist Radiol Surg*, vol. 10, no. 9, pp. 1461–1468, Sep 2015.

[42] S. Isotani, H. Shimoyama, I. Yokota, T. China, S. Hisasue, H. Ide, S. Muto, R. Yamaguchi, O. Ukimura, and S. Horie, "Feasibility and accuracy of computational robot-assisted partial nephrectomy planning by virtual partial nephrectomy analysis," *Int. J. Urol.*, vol. 22, no. 5, pp. 439–446, May 2015.

[43] D. Ueno, K. Makiyama, H. Yamanaka, T. Ijiri, H. Yokota, and Y. Kubota, "Prediction of open urinary tract in laparoscopic partial nephrectomy by virtual resection plane visualization," *BMC Urol*, vol. 14, p. 47, Jun 2014.

[44] P. Mozer, A. Leroy, Y. Payan, J. Troccaz, E. Chartier-Kastler, and F. Richard, "Computer-assisted access to the kidney," *Int J Med Robot*, vol. 1, no. 4, pp. 58–66, Dec 2005.

[45] P. Mozer, P. Conort, A. Leroy, M. Baumann, Y. Payan, J. Troccaz, E. Chartier-Kastler, and F. Richard, "Aid to percutaneous renal access by virtual projection of the ultrasound puncture tract onto fluoroscopic images," *J. Endourol.*, vol. 21, no. 5, pp. 460–465, May 2007.

[46] Z. C. Li, K. Li, H. L. Zhan, K. Chen, J. Gu, and L. Wang, "Augmenting intraoperative ultrasound with preoperative magnetic resonance planning models for percutaneous renal access," *Biomed Eng Online*, vol. 11, p. 60, Aug 2012.

[47] T. Oliveira-Santos, M. Peterhans, B. Roth, M. Reyes, L. P. Nolte, G. Thalmann, and S. Weber, "Computer aided surgery for percutaneous nephrolithotomy: Clinical requirement analysis and system design," *Conf Proc IEEE Eng Med Biol Soc*, vol. 2010, pp. 442–445, Aug 2010.

[48] J. J. Rassweiler, M. Muller, M. Fangerau, J. Klein, A. S. Goezen, P. Pereira, H. P. Meinzer, and D. Teber, "iPad-assisted percutaneous access to the kidney using marker-based navigation: initial clinical experience," *Eur. Urol.*, vol. 61, no. 3, pp. 628–631, Mar 2012.

[49] H. Li, Y. Chen, C. Liu, B. Li, K. Xu, and S. Bao, "Construction of a three-dimensional model of renal stones: comprehensive planning for percutaneous nephrolithotomy and assistance in surgery," *World J Urol*, vol. 31, no. 6, pp. 1587–1592, Dec 2013.

[50] M. Muller, M. C. Rassweiler, J. Klein, A. Seitel, M. Gondan, M. Baumhauer, D. Teber, J. J. Rassweiler, H. P. Meinzer, and L. Maier-Hein, "Mobile augmented reality for computer-assisted percutaneous nephrolithotomy," *Int J Comput Assist Radiol Surg*, vol. 8, no. 4, pp. 663–675, Jul 2013.

[51] K. Makiyama, M. Nagasaka, T. Inuiya, K. Takanami, M. Ogata, and Y. Kubota, "Development of a patient-specific simulator for laparoscopic renal surgery," *Int. J. Urol.*, vol. 19, no. 9, pp. 829–835, Sep 2012.

[52] K. Makiyama, H. Yamanaka, D. Ueno, K. Ohsaka, F. Sano, N. Nakaigawa, M. Yao, and Y. Kubota, "Validation of a patient-specific simulator for laparoscopic renal surgery," *Int. J. Urol.*, vol. 22, no. 6, pp. 572–576, Jun 2015.

[53] M. Baumhauer, T. Simpfendörfer, B. P. Müller-Stich, D. Teber, C. N. Gutt, J. Rassweiler, H. P. Meinzer, and I. Wolf, "Soft tissue navigation for laparoscopic partial nephrectomy," *Int J Comput Assist Radiol Surg*, vol. 3, no. 3-4, pp. 307–314, May 2008.

[54] D. Teber, S. Guven, T. Simpfendorfer, M. Baumhauer, E. O. Guven, F. Yencilek, A. S. Gozen, and J. Rassweiler, "Augmented reality: a new tool to improve surgical accuracy during laparoscopic partial nephrectomy? Preliminary in vitro and in vivo results," *Eur. Urol.*, vol. 56, no. 2, pp. 332–338, Aug 2009.

[55] K. Nakamura, Y. Naya, S. Zenbutsu, K. Araki, S. Cho, S. Ohta, N. Nihei, H. Suzuki, T. Ichikawa, and T. Igarashi, "Surgical navigation using three-dimensional computed tomography images fused intraoperatively with live video," *J. Endourol.*, vol. 24, no. 4, pp. 521–524, Apr 2010.

[56] H. O. Altamar, R. E. Ong, C. L. Glisson, D. P. Viprakasit, M. I. Miga, S. D. Herrell, and R. L. Galloway, "Kidney deformation and intraprocedural registration: a study of elements of image-guided kidney surgery," *J. Endourol.*, vol. 25, no. 3, pp. 511–517, Mar 2011.

[57] P. Pratt, A. Jaeger, A. Hughes-Hallett, E. Mayer, J. Vale, A. Darzi, T. Peters, and G. Z. Yang, "Robust ultrasound probe tracking: initial clinical experiences during robot-assisted partial nephrectomy," *Int J Comput Assist Radiol Surg*, vol. 10, no. 12, pp. 1905–1913, Dec 2015.

[58] M. S. Lasser, M. Doscher, A. Keehn, V. Chernyak, E. Garfein, and R. Ghavamian, "Virtual surgical planning: a novel aid to robot-assisted laparoscopic partial nephrectomy," *J. Endourol.*, vol. 26, no. 10, pp. 1372–1379, Oct 2012.

[59] A. Hughes-Hallett, P. Pratt, E. Mayer, S. Martin, A. Darzi, and J. Vale, "Image guidance for all–TilePro display of 3-dimensionally reconstructed images in robotic partial nephrectomy," *Urology*, vol. 84, no. 1, pp. 237–242, Jul 2014.

[60] Y. Xu, P. Shao, X. Zhu, Q. Lv, W. Liu, H. Xu, Y. Zhu, G. Yang, L. Tang, and C. Yin, "Three-dimensional renal CT angiography for guiding segmental renal artery clamping during laparoscopic partial nephrectomy," *Clin Radiol*, vol. 68, no. 11, pp. e609–616, Nov 2013.

[61] G. Spana, G.-P. Haber, L. M. Dulabon, F. Petros, C. G. Rogers, S. B. Bhayani, M. D. Stifelman, and J. H. Kaouk, "Complications after robotic partial nephrectomy at centers of excellence: multi-institutional analysis of 450 cases," *J. Urol.*, vol. 186, no. 2, pp. 417–422, 2011.

[62] A. Breda, A. Finelli, G. Janetschek, F. Porpiglia, and F. Montorsi, "Complications of laparoscopic surgery for renal masses: prevention, management, and comparison with the open experience," *Eur. Urol.*, vol. 55, no. 4, pp. 836–850, 2009.

[63] J. Xie, Y. Jiang, and H. T. Tsui, "Segmentation of kidney from ultrasound images based on texture and shape priors," *IEEE Trans Med Imaging*, vol. 24, no. 1, pp. 45–57, Jan 2005.

[64] A. Ahmad, D. Cool, B. H. Chew, S. E. Pautler, and T. M. Peters, "3D segmentation of kidney tumors from freehand 2D ultrasound," in *Medical Imaging 2006: Visualization, Image-Guided Procedures, and Display*, K. R. Cleary and J. Robert L. Galloway, Eds., Mar 2006.

[65] F. Yang, W. Qin, Y. Xie, T. Wen, and J. Gu, "A shape-optimized framework for kidney segmentation in ultrasound images using NLTV denoising and DRLSE," *Biomed Eng Online*, vol. 11, p. 82, Oct 2012.

[66] M. S. Nosrati, J. M. Peyrat, J. Abinahed, O. Al-Alao, A. Al-Ansari, R. Abugharbieh, and G. Hamarneh, "Efficient multi-organ segmentation in multi-view endoscopic videos using pre-operative priors," *Med Image Comput Comput Assist Interv*, vol. 17, no. Pt 2, pp. 324–331, 2014.

[67] M. S. Nosrati, R. Abugharbieh, J. M. Peyrat, J. Abinahed, O. Al-Alao, A. Al-Ansari, and G. Hamarneh, "Simultaneous Multi-Structure Segmentation and 3D Nonrigid Pose Estimation in Image-Guided Robotic Surgery," *IEEE Trans Med Imaging*, vol. 35, no. 1, pp. 1–12, Jan 2016.

[68] M. S. Nosrati, A. Amir-Khalili, J. M. Peyrat, J. Abinahed, O. Al-Alao, A. Al-Ansari, R. Abugharbieh, and G. Hamarneh, "Endoscopic scene labelling and augmentation using intraoperative pulsatile motion and colour appearance cues with preoperative anatomical priors," *Int J Comput Assist Radiol Surg*, Feb 2016.

[69] B. Rosa, P. Mozer, and J. Szewczyk, "An algorithm for calculi segmentation on ureteroscopic images," *Int J Comput Assist Radiol Surg*, vol. 6, no. 2, pp. 237–246, Mar 2011.

[70] J. A. Noble and D. Boukerroui, "Ultrasound image segmentation: a survey," *IEEE Trans Med Imaging*, vol. 25, no. 8, pp. 987–1010, Aug 2006.

[71] C. Li, C. Xu, C. Gui, and M. D. Fox, "Distance regularized level set evolution and its application to image segmentation," *IEEE Trans Image Process*, vol. 19, no. 12, pp. 3243–3254, Dec 2010.

[72] A. B. Benincasa, L. W. Clements, S. D. Herrell, and R. L. Galloway, "Feasibility study for image-guided kidney surgery: assessment of required intraoperative surface for accurate physical to image space registrations," *Med Phys*, vol. 35, no. 9, pp. 4251–4261, Sep 2008.

[73] R. Ong, C. L. Glisson, J. Burgner-Kahrs, A. Simpson, A. Danilchenko, R. Lathrop, S. D. Herrell, R. J. Webster, M. Miga, and R. L. Galloway, "A novel method for texture-mapping conoscopic surfaces for minimally invasive image-guided kidney surgery," *Int J Comput Assist Radiol Surg*, vol. 11, no. 8, pp. 1515–1526, Aug 2016.

[74] R. San Jose Estepar, C. F. Westin, and K. G. Vosburgh, "Towards real time 2D to 3D registration for ultrasound-guided endoscopic and laparoscopic procedures," *Int J Comput Assist Radiol Surg*, vol. 4, no. 6, pp. 549–560, Nov 2009.

[75] P. Edgcumbe, P. Pratt, G. Z. Yang, C. Nguan, and R. Rohling, "Pico Lantern: Surface reconstruction and augmented reality in laparoscopic surgery using a pick-up laser projector," *Med Image Anal*, vol. 25, no. 1, pp. 95–102, Oct 2015.

[76] R. Kingma, R. N. Rohling, and C. Nguan, "Registration of CT to 3D ultrasound using near-field fiducial localization: A feasibility study," *Comput. Aided Surg.*, vol. 16, no. 2, pp. 54–70, Feb 2011.

[77] C. Schneider, C. Nguan, R. Rohling, and S. Salcudean, "Tracked "Pick-Up" Ultrasound for Robot-Assisted Minimally Invasive Surgery," *IEEE Trans Biomed Eng*, vol. 63, no. 2, pp. 260–268, Feb 2016.

[78] G. A. Puerto Souza, M. Adibi, J. A. Cadeddu, and G. L. Mariottini, "Adaptive multi-affine (ama) feature-matching algorithm and its application to minimally-invasive surgery images," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Sept 2011, pp. 2371–2376.

[79] G. A. Puerto-Souza and G. L. Mariottini, "A fast and accurate feature-matching algorithm for minimally-invasive endoscopic images," *IEEE Trans Med Imaging*, vol. 32, no. 7, pp. 1201–1214, Jul 2013.

[80] G. A. Puerto-Souza, J. A. Cadeddu, and G. L. Mariottini, "Toward long-term and accurate augmented-reality for monocular endoscopic videos," *IEEE Trans Biomed Eng*, vol. 61, no. 10, pp. 2609–2620, Oct 2014.

[81] M. C. Yip, D. G. Lowe, S. E. Salcudean, R. N. Rohling, and C. Y. Nguan, "Tissue tracking and registration for image-guided surgery," *IEEE Trans Med Imaging*, vol. 31, no. 11, pp. 2169–2182, Nov 2012.

[82] E. Wild, D. Teber, D. Schmid, T. Simpfendorfer, M. Muller, A. C. Baranski, H. Kenngott, K. Kopka, and L. Maier-Hein, "Robust augmented reality guidance with fluorescent markers in laparoscopic surgery," *Int J Comput Assist Radiol Surg*, vol. 11, no. 6, pp. 899–907, Jun 2016.

[83] C. Glisson, R. Ong, A. Simpson, P. Clark, S. D. Herrell, and R. Galloway, "The use of virtual fiducials in image-guided kidney surgery," *Proceedings of SPIE 7964, medical imaging 2011: visualization. Image-guided procedures, and modeling.*, Mar 2011.

[84] P. Besl and H. McKay, "A method for registration of 3-D shapes," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 14, no. 2, pp. 239–256, Feb 1992.

[85] D. G. Lowe, "Distinctive image features from scale-invariant keypoints," *Int J Comput Vision*, vol. 60, no. 2, pp. 91–110, Nov 2004.

[86] M. Cho, J. Lee, and K. M. Lee, "Feature correspondence and deformable object matching via agglomerative correspondence clustering," in *2009 IEEE 12th International Conference on Computer Vision*, Sep 2009.

[87] M. Agrawal, K. Konolige, and M. R. Blas, "CenSurE: Center surround extremas for realtime feature detection and matching," in *Lecture Notes in Computer Science*, 2008, pp. 102–115.

[88] M. Calonder, V. Lepetit, C. Strecha, and P. Fua, "BRIEF: Binary Robust Independent Elementary Features," in *Computer Vision – ECCV 2010*, 2010, pp. 778–792.

[89] L. Maier-Hein, A. Groch, A. Bartoli, S. Bodenstedt, G. Boissonnat, P. L. Chang, N. T. Clancy, D. S. Elson, S. Haase, E. Heim, J. Hornegger, P. Jannin, H. Kenngott, T. Kilgus, B. Muller-Stich, D. Oladokun, S. Rohl, T. R. Dos Santos, H. P. Schlemmer, A. Seitel, S. Speidel, M. Wagner, and D. Stoyanov, "Comparative validation of single-shot optical techniques for laparoscopic 3-D surface reconstruction," *IEEE Trans Med Imaging*, vol. 33, no. 10, pp. 1913–1930, Oct 2014.

[90] R. E. Ong, S. D. H. III, M. I. Miga, and J. Robert L. Galloway, "A kidney deformation model for use in non-rigid registration during image-guided surgery," in *Medical Imaging 2008: Visualization, Image-guided Procedures, and Modeling*. SPIE-Intl Soc Optical Eng, Mar 2008.

[91] I. Figueroa-Garcia, J.-M. Peyrat, G. Hamarneh, and R. Abugharbieh, "Biomechanical kidney model for predicting tumor displacement in the presence of external pressure load," in *IEEE 11th International Symposium on Biomedical Imaging (ISBI)*, 2014, pp. 810–813.

[92] S. Nishiyama, Y. Kuroda, and H. Takemura, "Stiffness matrix representation of hyper-elasticity for surgical simulation and navigation," *Conf Proc IEEE Eng Med Biol Soc*, vol. 2015, pp. 905–908, Aug 2015.

[93] A. Hostettler, D. George, Y. Remond, S. A. Nicolau, L. Soler, and J. Marescaux, "Bulk modulus and volume variation measurement of the liver and the kidneys in vivo using abdominal kinetics during free breathing," *Comput Methods Programs Biomed*, vol. 100, no. 2, pp. 149–157, Nov 2010.

[94] Y. Naya, K. Nakamura, K. Araki, K. Kawamura, S. Kamijima, T. Imamoto, N. Nihei, H. Suzuki, T. Ichikawa, and T. Igarashi, "Usefulness of panoramic views for novice surgeons doing retroperitoneal laparoscopic nephrectomy," *Int. J. Urol.*, vol. 16, no. 2, pp. 177–180, Feb 2009.

[95] K. Makiyama, R. Sakata, H. Yamanaka, T. Tatenuma, F. Sano, and Y. Kubota, "Laparoscopic nephroureterectomy in renal pelvic urothelial carcinoma with situs inversus totalis: preoperative training using a patient-specific simulator," *Urology*, vol. 80, no. 6, pp. 1375–1378, Dec 2012.

[96] A. Hughes-Hallett, E. K. Mayer, H. J. Marcus, P. Pratt, S. Mason, A. W. Darzi, and J. A. Vale, "Inattention blindness in surgery," *Surg Endosc*, vol. 29, no. 11, pp. 3184–3189, Nov 2015.

[97] A. Hughes-Hallett, E. K. Mayer, P. Pratt, A. Mottrie, A. Darzi, and J. Vale, "The current and future use of imaging in urological robotic surgery: a survey of the European Association of Robotic Urological Surgeons," *Int J Med Robot*, vol. 11, no. 1, pp. 8–14, Mar 2015.

[98] A. Hughes-Hallett, P. Pratt, E. Mayer, M. Clark, J. Vale, and A. Darzi, "Using preoperative imaging for intraoperative guidance: a case of mistaken identity," *Int J Med Robot*, vol. 12, no. 2, pp. 262–267, Jun 2016.

[99] S. K. Warfield, K. H. Zou, and W. M. Wells, "Simultaneous truth and performance level estimation (STAPLE): an algorithm for the validation of image segmentation," *IEEE Trans Med Imaging*, vol. 23, no. 7, pp. 903–921, Jul 2004.

[100] Z. Liu, P. Wang, D. Xia, Y. F. Lou, H. F. Pan, and S. Wang, "Comparison between laparoscopic and open partial nephrectomy: surgical, oncologic, and functional outcomes," *Kaohsiung J. Med. Sci.*, vol. 29, no. 11, pp. 624–628, Nov 2013.

[101] B. R. Lane and I. S. Gill, "7-year oncological outcomes after laparoscopic and open partial nephrectomy," *J. Urol.*, vol. 183, no. 2, pp. 473–479, Feb 2010.

[102] H. G. Kenngott, M. Wagner, F. Nickel, A. L. Wekerle, A. Preukschas, M. Apitz, T. Schulte, R. Rempel, P. Mietkowski, F. Wagner, A. Termer, and B. P. Muller-Stich, "Computer-assisted abdominal surgery: new technologies," *Langenbecks Arch Surg*, vol. 400, no. 3, pp. 273–281, Apr 2015.

[103] U. Mezger, C. Jendrewski, and M. Bartels, "Navigation in surgery," *Langenbecks Arch Surg*, vol. 398, no. 4, pp. 501–514, Apr 2013.

[104] T. Okamoto, S. Onda, K. Yanaga, N. Suzuki, and A. Hattori, "Clinical application of navigation surgery using augmented reality in the abdominal field," *Surg. Today*, vol. 45, no. 4, pp. 397–406, Apr 2015.

[105] C. Schneider, C. Nguan, M. Longpre, R. Rohling, and S. Salcudean, "Motion of the kidney between preoperative and intraoperative positioning," *IEEE Trans Biomed Eng*, vol. 60, no. 6, pp. 1619–1627, Jun 2013.

[106] B. J. Dixon, M. J. Daly, H. Chan, A. D. Vescan, I. J. Witterick, and J. C. Irish, "Surgeons blinded by enhanced navigation: the effect of augmented reality on attention," *Surg Endosc*, vol. 27, no. 2, pp. 454–461, Feb 2013.

[107] T. Klatte, N. Kroeger, U. Zimmermann, M. Burchardt, A. S. Belldegrun, and A. J. Pantuck, "The contemporary role of ablative treatment approaches in the management of renal cell carcinoma (RCC): focus on radiofrequency ablation (RFA), high-intensity focused ultrasound (HIFU), and cryoablation," *World J Urol*, vol. 32, no. 3, pp. 597–605, Jun 2014.