Chapter 10

The Challenge of Augmented Reality in Surgery

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Abstract

Imaging has revolutionized surgery over the last 50 years. Diagnostic imaging is a key tool for deciding to perform surgery during disease management; intraoperative imaging is one of the primary drivers for minimally invasive surgery (MIS), and postoperative imaging enables effective follow up and patient monitoring. However, notably there is still relatively little interchange of information or imaging modality fusion between these different clinical pathway stages. This book chapter provides a critique of existing augmented reality (AR) methods or application studies described in the literature using relevant examples. The aim is not to provide a comprehensive review, but rather to give an indication of the clinical areas in which AR has been proposed, to begin to explain the lack of clinical systems and to provide some clear guidelines to those intending pursue research in this area.

Keywords: Augmented Reality, Virtual Reality, Image Guided Surgery, Navigation, Stereotactic Navigation, Digital Surgery, Surgery 4.0

Introduction

Imaging has revolutionized surgery over the last 50 years. Diagnostic imaging is a key tool for deciding to perform surgery during disease management; intraoperative imaging is one of the primary drivers for minimally invasive surgery (MIS), and postoperative imaging enables effective follow up and patient monitoring. However, notably there is still relatively little interchange of information or imaging modality fusion between these different clinical pathway stages [1].

Preoperative imaging provides three-dimensional (3D) digitization of internal patient anatomy and pathology which can be segmented and converted to surfaces in order to be displayed as a virtual model. The idea of presenting this model directly overlaid on the surgeon's view of the surgical site during procedures has been around for several decades, with solutions being proposed in the neurosurgical microscope as early as 1982 [2] and in head-mounted displays in 1996 [3]. Since these early beginnings there has been a steady increase in research interest around both the technology and the clinical translation of such systems. An excellent overview of the current state of the art in terms of the technology is provided by the book by Peters et al. [4] and recent reviews on the topic [5, 6].

Augmented reality (AR) devices can be broadly split into two groups – video based AR and optical see-through AR (Fig. 10.1). Literature around the former is dominated by efforts in MIS and laparoscopic procedures, which are very amenable to AR when performed either with hand-held instrumentation [5] or with robotic systems such as the da Vinci Surgical System® (Intuitive Surgical Inc., CA) [7].

Optical see-through AR, which began with surgical microscope systems, has had a resurgence of interest due to the prevalence of wearable AR head-mounted displays, such as the

Microsoft Hololens™; but recent studies still suggest that more work is needed, especially in hardware to make the technology more effectively applicable to surgery [8].

Though the idea that an overlay combining information from different imaging modalities should provide direct and ergonomic visualization seems reasonable, such AR visualizations have not yet made it into mainstream clinical practice. Indeed, while there have been many initial demonstrations of AR guidance, in the laboratory and in the operating room (OR), there have been only a few attempts to investigate clinical effectiveness of the systems developed. In such cases, the clinical utility of direct overlay on the surgical view is often not clear or not proven and there have been very few examples of successful products incorporating AR.

This book chapter provides a critique of existing AR methods or application studies described in the literature using relevant examples. The aim is not to provide a comprehensive review, but rather to give an indication of the clinical areas in which AR has been proposed, to begin to explain the lack of clinical systems and to provide some clear guidelines to those intending pursue research in this area.

We start by describing the two broad categories of AR, video see-through and optical see-through, within a historical context of the field. We then go on to examine the components that make up an AR system, in each case examining aspects of this component that may provide barriers to introduction in the clinic (Fig. 10.2). Finally, we make the case for increased research in human perception and effect on performance in the virtual and lab settings, as well as task-focused applications in the operating room. With the ready availability and increasing quality of visualization devices it seems likely that interest in this area will continue to increase. We hope this chapter is helpful in informing and guiding researchers in this field towards clinically effective products.

Historical Context

AR guidance of surgery was first proposed in 1982 by Kelly et al. [2], who overlaid tumor outlines from CT into the view of a surgical microscope attached to a stereotactic frame. A few years later, Roberts et al. took this further by incorporating an ultrasonic tracking system [9]. Despite significant errors of > 5cm these efforts are considered to be the beginning of frameless stereotaxy in neurosurgery, which is now more commonly called image-guided surgery and is routinely used for treatment of conditions in the brain [4].

AR overlay in the surgical microscope became part of the Zeiss MKM robotic microscope system, providing similar views to those originally proposed by Kelly et al. [2]. Augmented reality representation providing 3D visualization of preoperative imaging models was also proposed within the surgical microscope for ENT and neurosurgery [10]. Such augmented views are now available in surgical microscope products including the Zeiss Kinevo® 900 and the Leica ARveo in conjunction with image guidance systems such as BrainLab's neurosurgical microscope navigation product [11].

Such microscope-based systems are examples of optical see-through (OST) AR, in which the overlaid information is projected onto the optical view using a half-silvered mirror. The structure of an OST-AR system is shown in Figure 10.3. There has been a resurgence in interest in OST-AR with the introduction of commercial head-mounted devices such as the Microsoft Hololens 2™(www. microsoft.com/en-us/hololens) and the Magic Leap One™(www.magicleap. com).

In contrast to optical see-through systems, Fuchs et al. developed a camera based head mounted display system for guidance of breast and tumor biopsy in 1996 [3]. The system combined a virtual reality (VR) headset linked to calibrated stereo video cameras and was able to show the ultrasound image visualized coming physically out from the end of the probe. This initial system was further developed for breast tumor aspiration a couple of years later and demonstrated on phantoms and in four clinical cases [13]. This was the first video AR device for surgical guidance. A schematic showing how video AR is achieved is shown in Figure 10.4, where the virtual and real views are mixed on computer and then displayed to the surgeon.

The more recent literature for video-based surgical AR is dominated by the da Vinci Surgical System (Intuitive Surgical Inc., CA, USA). The robot was originally developed for cardiac procedures, specifically to perform totally endoscopic coronary artery bypass (TECAB), and AR has been proposed for such operations using a 4D cardiac CT model [14]. This was extended to potentially compensate for cardiac motion using dynamic information from the video feed and finite element modelling [7]. However, cost-effectiveness was not readily demonstrated for TECAB and clinical focus for the robot has shifted to urology, with prostatectomy and partial nephrectomy becoming commonly performed procedures, as well as, gynaecological surgery like robotic hysterectomy. Accordingly, AR focus shifted towards these application areas [15].

A recent comprehensive review of AR in robot-assisted surgery is provided by Qian et al. [16]. Despite taking into account 93 relevant papers over 19 years of research, they state that the field of AR in robotic-assisted surgery is not yet mature and clinical effectiveness remains to be proven. This conclusion is reiterated by a systematic review of AR in urological procedures [17]. The automatic provision of segmentation services for renal cancer is provided by companies such as Innersight Labs Ltd. (https://www.innersightlabs.com), Visible Patient (visiblepatient.com), Ceevra Inc. (https://ceevra.com) and Intuitive Surgical Inc. (intuitive.com) through their da Vinci Iris app. These products should enable much greater use of AR in the OR and lead towards a clearer understanding of the clinical effectiveness and best modes of operation for robotic AR surgical guidance.

In addition to robotic procedures, video-based AR has been proposed for non-robotic laparoscopic procedures (Fig. 10.5). Providing guidance during laparoscopic liver resection has attracted significant effort from both research [18, 20] and industry [21]. In laparoscopic gynaecology, Bartoli et al. have proposed an AR system for surgery of the uterus [22]. Neurosurgery, with the desire for accuracy and comparatively rigid anatomy encased within the cranium is a well-suited candidate for image guidance and Meola et al. provide a comprehensive review of this area [23].

A Google Scholar search for “augmented reality and surgery” produces the graph in Figure 10.6. The increase in research interest in AR is clear, with almost 5000 papers in 2019 and the trend is still upwards. This significant research effort has not yet been matched by AR products becoming commonplace in the operating room through there are indications that such systems may not be in the distant future. For example, Philips and Microsoft recently announced a collaboration to develop AR solutions for the operating room combining imaging technology and the Hololens™platform [24]. The VSI solution from apoQlar GmbH offers integration of care into the augmented view, including facial surface alignment for AR guidance of sinus surgery (see Fig. 10.3d,e). The Scopis system also provides AR visualisation for endoscopic sinus surgery (https://navigation. scopis.com/tgs). It is likely that interest in AR for surgical applications will continue to grow.

In the remainder of this chapter we consider the stages required to produce accurately aligned AR - preoperative model construction, calibration, registration, tracking and visualisation. In each instance, we consider how it is achieved, what research problems remain and whether these problems are likely to be a reason for the lack of clinical uptake of AR.

Preoperative Patient Data Acquisition and Model Construction

An example segmentation of a CT scan can be seen in Figure 10.7. The blood vessels supplying the kidney are segmented along with the lesion itself and the ureter. This model is intended for guidance of robotic-assisted partial nephrectomy. Identifying the relevant anatomy and physiology has traditionally been achieved by marking structures either by hand or in a semi-automated fashion in each of the image slices. A number of free or open-source packages are available to help with this process, including Slicer (https://www. slicer.org/), ITKSnap (http://www.itksnap.org/), Osirix (https://www. osirix-viewer.com/) and ImageJ (https://imagej.net/). These packages are helpful, but not quite ready for routine clinical use to generate anatomical models for AR visualization. The main additions needed to such software packages are greater automation of segmentation to alleviate the time needed for clinicians to generate the AR model and also customization for specific organs and modalities to ensure high fidelity models are generated across different surgical specialties.

The research area of image segmentation is substantial and is becoming more mature as automated identification of structures is improving using deep learning [25]. The image shown in Figure 10.7 depicts a model from Innersight Labs Ltd. Such services or automated segmentations, though currently focused on the kidney, will hopefully become more readily available in other clinical application areas.

AR surgical guidance provided by preoperative 3D imaging firstly requires that preoperative imaging is able to provide information that is useful to the surgery being performed. Deep learning is leading towards automated segmentation of images that is approaching the performance of expert radiologists [25]. However, despite its great promise and considerable research effort, automated segmentation methods have not yet made in into regular clinical practice. This presents a significant challenge to the surgical workflow for AR guidance. The other question is whether preoperative imaging provides the desired information and also whether the anatomical and pathological structures can be readily identified in the scans. Taking examples from robotic procedures, in partial nephrectomy the models obtained from CT and CT angiography provide the general shape of the kidney and the structure of the feeding arteries that must be clamped before lesion removal. The tumor itself can also be seen, though the accuracy with which the tumour boundary can be delineated in the parenchyma has not yet been established. The CT model may speed up the process of vessel identification and could also help in tumor delineation in conjunction with laparoscopic ultrasound [26].

For radical prostatectomy the principal structure of interest is the neurovascular bundle, since preservation of the nerves and blood vessels will result in improved postoperative function. But this structure is not readily and accurately found in preoperative imaging, which makes the case for AR guidance less clear for this procedure [15]. With the adoption of new imaging agents or hybrid imaging techniques like PET-MRI this issue may be alleviated. This is a key criterion for successful future applications of AR. *One must consider whether preoperative imaging can provide the relevant critical information that can help guide surgery.* This is the first consideration that should be taken into account when proposing AR in any new clinical specialisation.

Optical Calibration

Calibration is a key component of the software for AR systems allowing the transformation of information between the different coordinate frames of the environment, sensors and the AR model. The standard procedure is to calibrate the surgical camera to establish correspondence between 3D space of the surgical site and the video image from the camera sensor. There are standard implementations in OpenCV and MatLab that tend to be used [27, 28]. For video see-through, the methods for calibration are well-established and most studies suggest that registration is a larger source of error [29] but perhaps new constraints that incorporate the position of the trocar point can reduce error [30].

Calibration for OST devices such as the Hololens™ is more complex. In the case of theHololens™, sensors on the device create a model of the room and objects are placed within this coordinate system. In order to anchor an object to a specific location in the room, optical tracking markers have been proposed, such as the ARToolkit markers or the image-based tracking provided by Vuforia [31]. Such methods perform tracking through the same sensors as those used for head tracking; calibration should be straightforward or even unnecessary. However, one must rely on the manufacturer's calibration to the individual user's vision. In addition to single user calibrations, it is possible to have multiple users, each wearing a Hololens™, to interact together by viewing the same object in the same place anchored to a reference frame in the room. There remains a paucity of data examining the accuracy of this and while this is great for collaborative working, we are not aware of this aspect of the Hololens™being used for surgery guidance. The spinal surgery guidance system from

Augmedics (https://www.augmedics.com/) enables collaborative AR guidance using their customised visualisation system (see Fig. 10.3c).

Registration of the Preoperative Model to the Patient

In order to align the preoperative imaging model to an AR view, it is first necessary to align the imaging model to the physical space of the surgical site or patient. This is may be achieved with markers, either passive or active, and these can be either fixed to the anatomy (e.g. bone implanted) or attached using adhesives. Fiducial markers allow a straightforward calculation of the transformation between the different coordinate frames if they can be reliably detected, but practically such systems can suffer from occlusions or line of sight problems even in commercially available navigation systems such as BrainLab's surgery products (https://www.brainlab.com/surgery-products/) and the StealthStation™from Medtronic [32].

Markerless registration algorithms to align the surgical video feed to preoperative models have been the topic of many research systems and papers [18, 22, 33–35]. Despite great process in such technology and advances all aspects of the required algorithms - real-time performance, biomechanical deformation and realism, accuracy and robustness - fully automatic clinical solutions are still not readily available. *This aspect of AR is crucial because registration accuracy may be a key factor in the lack of uptake of AR.* In their critical systematic review of the literature for urological procedures, Bertolo et al. identify registration accuracy as the major limitation of AR [17].

However, even with perfect registration demonstrated in a virtual system, AR may not be the most effective visualization. Dilley et al compared AR with nearby virtual rendering and no guidance, finding that nearby virtual rendering was more effective than AR and no guidance [36]. This suggests that accurate registration is not the sole cause of AR's limitations.

Tracking

Live tracking and update of the image as the surgeon's view changes is required for accurate AR as the scene and the observer change their relationship. In the case of robot-assisted procedures the camera motion can potentially be provided by the robot kinematics although correction is likely needed because error propagates between the robot encoder coordinates and the camera frame [30]. For non-robotic MIS an external tracker is usually attached to the proximal end of the laparoscope and used to estimate the camera motion [18]. However, for optical tracking, it has been recognized that the distance between the tracker and the camera position can cause significant errors. This has led to interest in improving tracking using the endoscope visual view [37–39] and potentially mapping the entire surgical scene at the same time in structure from motion (SfM) or simultaneous localisation and mapping (SLAM) frameworks [40, 41].

Poor tracking may be problematic for guidance accuracy because a registered AR model may drift out of alignment. The relatively slow movement of the camera in robotic procedures make this less of an issue and the robot also provides camera positional information from the kinematics of the system. Even with hand-held laparoscopic surgery the camera tends to be held reasonably steady.

With head-mounted displays even a relatively small amount of lag can cause lack of comfort or even nausea. One of the main advantages of the Hololens™ is that substantial R&D

has gone into improving accuracy and reducing latency in the head tracking and positional mapping of the environment to alleviate this precise problem.

Intraoperative Visualisation

Having calibrated the optics and aligned the model correctly to the patient, it remains to decide on the most effective visualization for AR during surgery. In minimally invasive surgery where direct access or visualization of the anatomy is not possible or in microsurgery, the inherent use of a display facilitates AR visualization. In open surgery or orthopaedics an AR display needs to be incorporated into the process (see Fig. 10.3c and Fig. 10.5c,d). In addition to the display a number of additional considerations are important for surgical AR displays including fidelity of depth visualisation and minimisation of the information presented to avoid overload [42, 43]. Overall, it appears that visualisation and issues surrounding perception and interaction are in fact the biggest issues facing AR surgical guidance [44]. Below we discuss in a little more detail some of the challenges.

Depth Perception

Even with correct alignment and well calibrated stereo views or other means of 3D scene mapping, there are remaining issues of depth perception that have been investigated in the general field of human vision [45]. This is also recognized as a significant problem in surgical applications [46]. In general, the perceived relative depths of the real and virtual objects become distorted as they approach the same depth, *an effect known as depth-contrast.* This is an area that deserves more attention, as the direction of the distortion has been observed differently in different experiments [45, 47]. It is possible some of these effects can be reduced or perhaps alleviated entirely with the correct level of mixing, adjustment of visual parameters such as spatial frequency or color and incorporation of other visual cues such as motion. Techniques such as inverse realism has also been proposed to help make the real surface look transparent in video-based AR, where the real surface can be partially blacked out to make perception of underlying structures more natural [48, 49]

Fatigue

It has been recognized in both virtual and augmented displays that, over a period of time, the use of the device may cause fatigue or lack of comfort in the user. Symptoms such as tiredness, dizziness or even nausea have been reported [50, 51]. The cause has not been fully established, but it has been suggested that lag between head motion and movement of the virtual scene could be a factor as well as inconsistency between the focus and convergence of binocular vision [52]. Issues that occur for virtual reality displays are equally a problem for AR and can be attributed to the display resolution, refresh rate, brightness and other characteristics [53]. Efforts from the VR community to alleviate fatigue in wearable consumer systems for gaming may provide useful ideas to address this in surgery. Examples include a dynamic depth-of-field [54] and focal surface displays [55].

Visual Clutter

Possibly the biggest challenge for AR as a method of surgical guidance is that it adds clutter to the scene. The visualization in Figure 10.8 demonstrates the problem, where the tools are obscured by the solid AR view. This issue is specifically documented by Dixon et al. [56]

and Hughes-Hallet et al. [57] and is also recognised in Qian's review of robotic AR, where they suggest that methods such as activation-on-demand can be used to reduce visual clutter [16].

Future Directions

AR Display Technology

In the MIS or microsurgery setting, the display of fused information is naturally accommodated by the inherent presence of a digital monitor showing the surgical camera feed. However, displays are a major technological area for further development to allow AR in other procedures or where a surgical camera is not present. See through mirror displays or video-see through displays could be brought in to enable visual information overlay [58]. These could be enhanced through different display technologies to support, for example, better depth perception without immersive consoles using autostereoscopic displays or visualization directly on the patient through projection of information onto the surgical site [59].

Interventional Imaging

It is possible to augment views other than the optical view of the patient in procedures where different energy levels are used to image the anatomy. This is particularly relevant in endovascular surgery or interventional radiology where flouroscopy is used to see the internal anatomy. Overlays of information from CT onto the fluoroscopic image can guide treatment in a range of procedures supporting better stent placement or valve replacement and meanwhile reducing the time taken for the procedure and thus the radiation dose. Figure 10.9 shows the overlay of preoperative CT accurately aligned to the fluoroscopic view using the Cydar EV system (https://www.cydarmedical.com/product). Live deformation is performed in the cloud to provide accurate and reliable alignment. This is an example of a system where live radiological images can be augmented using preoperative models.

Live imaging can also be used to augment the endoscopic view. Examples of this include the da Vinci Firefly fluorescence imaging seen in Figure 10.10. Fluorescence imaging can provide live visualization of metabolism, showing the location of blood vessels or cancerous tissue [60, 61]. Blood vessels may also be identified by analytic methods such as video amplification [62]. The use of such live imaging modalities alleviates the need for model registration and it is likely that these methods will have a significant role in future surgical practice. But it will still be important to develop systems that can optimize the displayed information by making use of all relevant contrasts of specific structures that are available across the different modalities.

Conclusions and Recommendations

In this chapter, we have outlined the methods and applications employed to achieve AR for surgical guidance and navigation. Although there have been some systems that have demonstrated potential clinical advantages of using AR in small numbers of cases, there are clearly challenges that remain both in the underpinning technology and in clinical translation to fit AR with current clinical processes. It should be added that a significant proportion of the papers in the graph shown in Figure 10.6 detail attempts to address some of the technical or algorithmic challenges in AR visualisation or registration. Yet few papers address in detail the clinical practicalities and possible barriers in underpinning technology such as in medical image segmentation and pre-processing which, despite tremendous advances, is still not routinely available for all anatomical regions. Other technical challenges remain, such as in the level of maturity of wearable AR devices and their restricted applicability to surgery [44].

We suggest that there is a need to perform experiments in the laboratory to establish the utility of AR for specific tasks. Figure 10.11a-d shows a very stylized kidney phantom. Such models can be produced relatively cheaply and incorporated into a training curriculum, allowing a significant number of experiments to establish the effectiveness of AR visualization without posing a risk to patients. The phantom shown here is not realistic, but may be sufficient to show whether AR can improve outcomes such as surgical margins in the laboratory setting.

There may also be a case for incorporating much more realistic phantoms (Fig. 10.11e) into the surgical training curriculum in the future, enabling trainees to practice in a realistic setting without risk to patients [63]. Such a platform would also allow safe investigation of the effect of AR visualization on surgical training and practice.

When considering AR as visualization methodology for any particular surgical application, we recommend considering the following issues:

- What is the real clinical problem being addressed and is AR the most appropriate technology to tackle it?
- Is the underlying data needed available? For example, are the structures of interest seen in MRI or CT, and are they of sufficient resolution?
- • Is clinical workflow, for example pre-processing of the data, suitable and who will prepare models prior to surgery?
- How is AR likely to help? Accuracy? Speed? Reduction of errors? Decision making?

- What visualisation strategy is the most appropriate? Side-by-side? Mixed? OST or video AR?
- Aim to demonstrate improved performance in a virtual or phantom environment.
- When should AR visualisation be provided (which sections of the procedure, only on-demand)?

With a focus on finding the appropriate visualization to produce proven improvements in performance and decision making for specific surgical tasks, we believe that AR will find its correct place in surgery and improved outcomes for patients will result. Significant research effort will still be required to achieve this goal and it is likely that the effort in this area will continue to grow, taking advantage of continued improvements in surgical AR technology including both hardware and software. We hope this chapter helps to guide those working in this field towards measurable improvements in surgical performance and clinical outcomes.

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Figure Legends

Fig. 10.1. Augmented reality devices in surgical applications. In the top row we have an optical see-through AR example, showing segmented preoperative MRI (**a**), the head-mounted display (Microsoft Hololens™) in colorectal surgery (**b**) and the surgeon's view with overlay (**c**). Below is a video see-through example, showing preoperative segmented CT (**d**), the da Vinci Robot console (**e**) and overlay of the kidney model through the console during partial nephrectomy (**f**).

Fig. 10.2. Schematic of the system layout for AR, showing how the different technical components of an AR system that we describe in the chapter are connected.

Fig. 10.3. The layout for an optical see-through (OST) AR system (**a**). A purely virtual view is overlaid on the surgeon's direct optical view using a half-silvered mirror. Examples include the PerkStation for CT needle guidance (**b**) and the Augmedics XVision system for spinal surgery (**c**). The VSI overlay system from apoQlar (https://apoqlar.com/) uses facial surface alignment to guide sinus surgery using the Hololens™(**d**,**e**) (Images courtesy of apoQlar GmbH)

Fig. 10.4. Video-based AR systems. A video camera takes a live image of the patient, which is mixed with a virtual view on a computer before being displayed to the surgeon.

Fig. 10.5. Registration of virtual and augmented views. The SmartLiver system [18] showing a rendering of the endoscope position relative to the patient anatomy (**a**) and the liver outline, underlying vessels and lesion from CT overlaid on the endoscopic view (**b**). Alignment is

achieved with surface matching. The orthopaedic guidance system of Pratt et al. [19] uses manual alignment to overlay a virtual view of bones and blood vessels (**c**) on the surgeon's view of the patient using the Hololens™ (**d**).

Fig. 10.6. Google Scholar search results for "Augmented reality" and "surgery" in the last 20 years

Fig. 10.7. Example CT segmentation of a kidney tumour. Voxels are labelled in the 3 orthogonal cuts and a 3D rendered model is constructed (bottom left). Blood vessels, ureter, kidney and lesion are visible (Model courtesy of Innersight Labs Ltd. displayed in ITKSnap)

Fig. 10.8. A scene from a robotic-assisted partial nephrectomy with no overlay (**a**), transparent overlay (**b**) and solid overlay (**c**), using the CT model from Fig. 10.7. The figure underlines the need to provide appropriate mixing of the virtual and real so as not to obscure or distract from the surgeon's view.

Fig. 10.9. The Cydar system, showing a CT model overlaid on X-ray for guidance of interventional procedures. The CT model is first aligned rigidly (**a**) and then deformed to match the therapeutic position of the patient (**b**). The alignment allows correct identification of vessels and reduces X-ray dose and clinical errors (Images reproduced with permission from cydarmedical.com)

Fig. 10.10. Images from the Firefly system, showing the endoscopic view (**a**), and overlays of live fluorescence imaging with different thresholds (**b,c**) which can provide a view of blood vessels or tumour metabolism directly on the surgeon's view. Such live views alleviate the need for registration.

Fig. 10.11. A stylized kidney phantom, showing the phantom (**a**), CT scan (**b**), virtual model (**c**) and AR overlay (**d**). Though the phantom is not anatomically realistic, it can be readily manufactured to enable experiments in the lab that can demonstrate the accuracy of lesion extraction with different visualizations. Anatomically and physically more accurate phantoms (**e**) can enable realistic and safe surgical rehearsal of AR systems.