Three-dimensional imaging in urology

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INTRODUCTION

Bestowed with binocular vision, humans can appreciate the world around them in three dimensions. As any student of anatomy knows, a real understanding and appreciation of anatomical relationships comes with studying cadavers or three-dimensional (3D) models. Until recently medical imaging was limited to 2D projections of these relationships, but within the last decade advances in cross-sectional imaging technology, combined with an exponential rise in processing power, has allowed it to portray human anatomy in 3D. Many clinicians may not be aware that even the trusty portable bladder scanners presently use 3D ultrasound technology.

3D imaging is likely to have a major impact on many aspects of future investigation and management [1]. This article reviews the current status of 3D imaging in urology and aims to provide some insight into what the future may hold.

3D RECONSTRUCTION

The production of a 3D image involves a stepwise sequence of data acquisition, interpolation, rendering and visualization [2]. First and foremost, data must be acquired as a complete volume, i.e. its orientation in the three spatial planes (*x, y, z*) needs to be registered. For CT and MRI this is not difficult, as the relationship of the scanner table to the scanning plane is always known (the *z* axis). As the table moves through the scanner, volumetric data are acquired.

However, ultrasonography (US) lacks orientation in the *z* axis (the non-imaging plane, Fig. 1) and therefore for 3D reconstruction positional orientation devices are necessary for registering the spatial co-ordinates of each US image. These devices can be mechanized or not, with their respective scanning techniques referred to as fixed or freehand. Mechanized systems use external or internal motors that move the ultrasound transducer in a predetermined manner (usually a curved sweep), whilst the probe is kept fixed over the region of interest (e.g. rotational movement during prostatic 3D US). Non-mechanized systems impose no restrictions on probe movement, using acoustic, electromagnetic or optical positional orientation devices to register the co-ordinates of each US image recorded.

US-acquired sequential images presently produce gaps in volume data which are rectified by a process known as interpolation. This involves a computer algorithm that effectively 'fills in the blanks' and produces the final 3D dataset [2]. US images frequently contain artefacts, making smooth interpolation difficult. This can result in incorrect 3D datasets and therefore the subsequent 3D reconstructed image will not be a true representation of the anatomy. This stumbling block is one of the main reasons why use of 3D US has lagged behind 3D CT and 3D MRI, although recent machines have advanced significantly in addressing this issue.

Once the final 3D dataset is obtained various techniques can be used to produce the computer-rendered 3D images. These images are reviewed on dedicated workstations that enable the clinician to manipulate and extract the information required.

RENDERING TECHNIQUES

Rendering is the process of mapping a 3D dataset onto a 2D screen for display. Although rendered images contain no more information than conventional axial images, they offer a more rapid appreciation of spatial information and anatomical relationships. Table 1 provides a brief description of the different rendering methods used, and Figs 2 and 3 some example images.

Surface- or volume-rendered data can be further explored with the technique of perspective rendering, in which the computer simulates an endoscopic view of a hollow viscus or body cavity; the so-called 'virtual endoscopy'. To create images of the interior of a lumen there must be either a naturally present high visual gradient between tissues (such as air next to bowel) or sufficient contrast material to allow differentiation between structures. In the urinary tract this has been possible by opacification with contrast medium or insufflation with air or CO_2 (Fig. 4).

Virtual endoscopy has inherent advantages in that it allows visualization of regions that are difficult to access, either anatomically or through disease (e.g. strictures), as well as avoiding complications such as perforation, stricture formation or infection. It offers the ability to look inside and outside the viscus, and is proving a useful tool in other specialities, including lower gastrointestinal endoscopy [3]. It is likely that the term 'virtual endoscopy' will soon be further defined with the prefix CT/MR/US, depending on the imaging method used.

CLINICAL APPLICATIONS OF 3D CT AND 3D MRI

CT/MR LOWER TRACT ENDOSCOPY

Because it has a simple morphology, ease of access and lack of peristalsis, the bladder was the first urinary tract organ to be assessed by virtual endoscopy. The bladder can be visualized using air, CO_2 [4] or intravenous contrast media [5]. Most earlier CT studies used thick CT slices for reconstruction, with perspective surface rendering, and therefore produced poor results that were not good at discriminating sessile/flat lesions or lesions of <5 mm [4]. Also, the insufflation technique was invasive and this drawback eliminated the potential advantage of virtual over conventional cystoscopy.

Improved results have subsequently been obtained using intravenous contrast agent, multidetector row CT (MDCT) and volume

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rendering [5]. Kim *et al.* [5] scanned 73 patients before cystoscopy and obtained 95% sensitivity and 87% specificity for all bladder lesions, with excellent intraobserver variability; 88% of lesions of <5 mm were detected, as well as 83% of sessile lesions.

MR cystoscopy is also feasible [6]. With MR a distended bladder filled with urine is sufficient for imaging, avoiding the need for catheterization or intravenous contrast agents. In a recent study, surface-rendered MR cystoscopy detected all bladder lesions of >1 cm, but performed less well with smaller lesions, detecting only 70% of lesions <1 cm [6]. Because it has poorer spatial resolution and higher costs, MR is unlikely to overtake CT cystoscopy in the foreseeable future.

Limitations of virtual cystoscopy include the inability to biopsy and the lack of mucosal detail [4,6]. In addition, intravenous contrast agents and ionizing radiation carry inherent risks. It therefore seems unlikely that virtual cystoscopy will replace cysto-urethroscopy, but it may have a role in difficult cases and provide supplementary information of possible bladder disease when investigating upper tract disease.

CT/MR UPPER TRACT ENDOSCOPY

Virtual endoscopic studies of the upper tract to date are limited. Only a few patients have been studied and out-of-date surface rendering techniques used [7–9], but they did show early promise. CT nephroscopy detected 92% of renal pelvis urothelial tumours, vs 83% for axial CT [7], when compared to histopathological specimens. CT ureteroscopy has a sensitivity of 81% and specificity of 100% for ureteric tumours [8]. Again, as with virtual cystoscopy, sessile lesions were more difficult to detect than pedunculated lesions. Examination with MDCT and perspective volume rendering may produce better results.

Neri *et al.* [9], using non-contrast MR endoscopy, showed that navigation through the renal pelvis, calyces and ureter (if the diameter was >5 mm) was feasible when urinary tract obstruction was present. Various neoplastic lesions, calculi and strictures were detected, being confirmed on conventional endoscopy [9]. A current limitation of MR and CT uro-renoscopy is that it requires relatively capacious collecting systems, e.g. in the study by Neri *et al.* navigation failed in half the unobstructed/undilated systems. This limitation may be overcome by continuing improvements in imaging hardware and software.

*FIG. 1. The z axis in volumetric imaging: **a,** CT/MR obtains volumetric data whilst the patient is pushed through the z axis by the table. **b,** US lacks orientation in the z axis; position and orientation of the transducer is required to acquire volumetric data.*

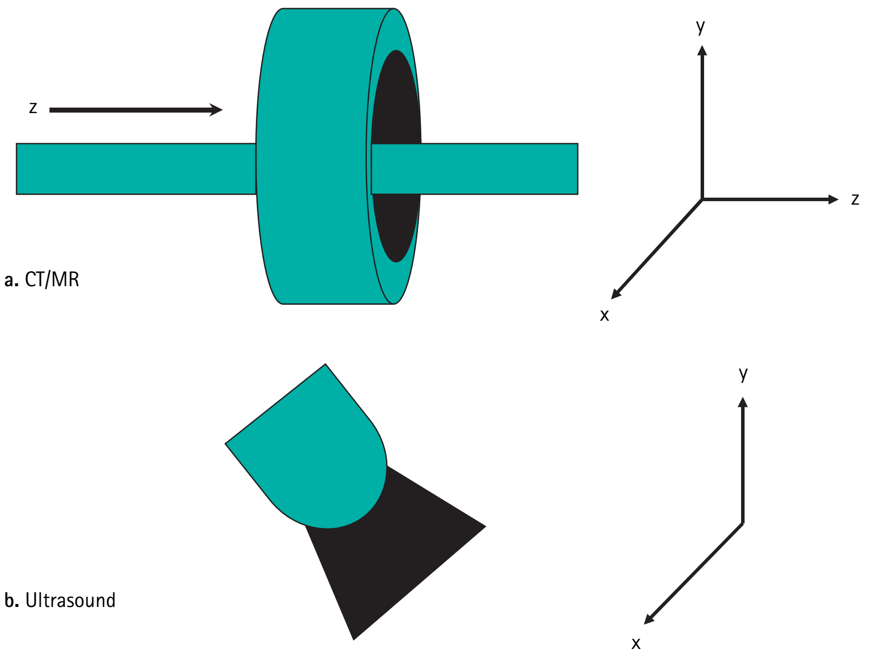


TABLE 1 Common 3D rendering methods

Rendering method	Description	Application
Maximum intensity projection	Flat image of volume with only the brightest voxels (volume elements) displayed. Good for displaying high attenuation arteries or calculi	CT angiography CT urography
Multi-planar reformatting	Image of any arbitrarily chosen plane acquired by dissecting the volume block. Reveals images that would not normally be seen due to scanning restrictions	3D TRUS (viewing of 'coronal' plane)
Surface rendering	Volume image with apparent surfaces, shaded in different densities, giving depth appreciation. Uses only 10% of available volume and sacrifices fine detail.	CT/MR cystoscopy CT/MR uro-renoscopy
Volume rendering	Higher fidelity images that use all available volume. Allows greater control of structures with varying attenuation with the capacity to selectively alter the opacity of voxels	CT/MR cystoscopy CT/MR uro-renoscopy 3D Operative Navigator

SURGICAL PLANNING

RENAL SURGERY

3D CT rendered images on a workstation provide an interactive display combining axial

FIG. 2. 3D CT of the renal tract, maximum intensity projection; the CT equivalent of the IVU.

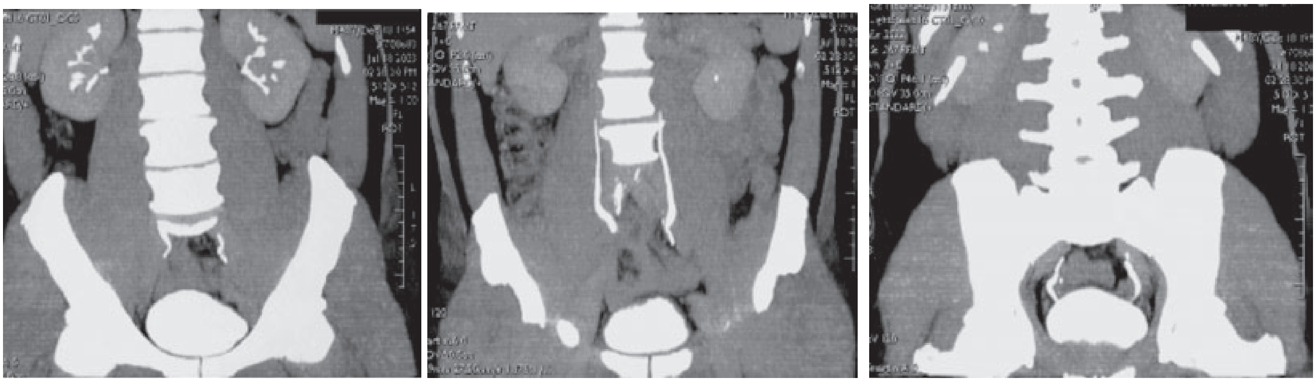
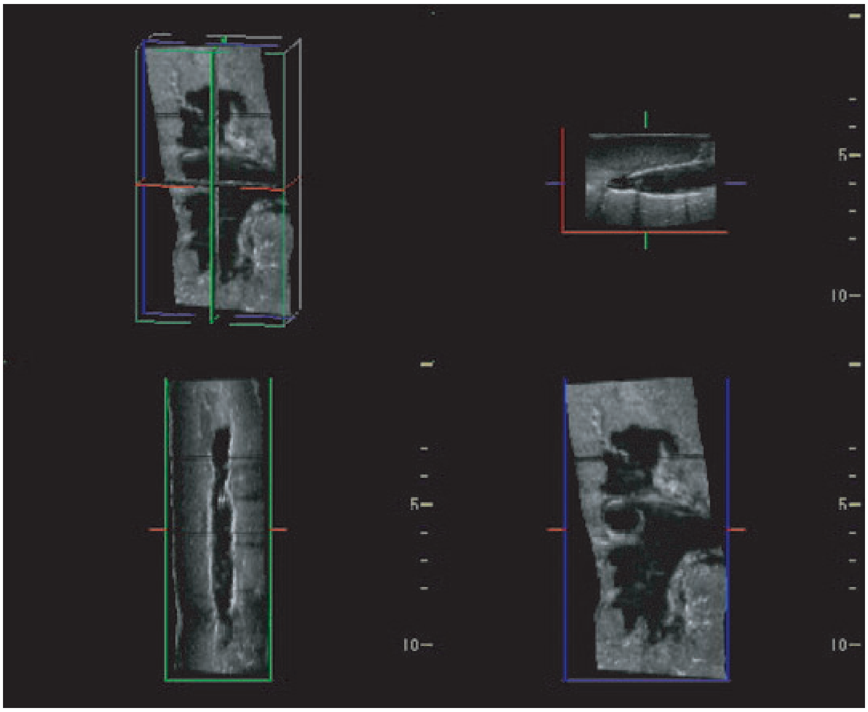


FIG. 3. Renal 3D US; multi-planar reformatted images of a pig kidney.



CT, excretory urography and angiography. Relevant features of a renal tumour, its relationship to the parenchyma, collecting system and vascular tree, are displayed in a manner easily understandable to the surgeon [10,11]. This detailed visual feast becomes even more valuable to the surgeon embarking upon nephron-sparing surgery (NSS). Volume-rendered 3D CT reconstruction of renal tumours before NSS is now routine in certain centres, and when applied to 60 such patients this technique detected all lesions accurately, along with 96% of renal arteries and 93% of renal veins [10]. Pre-nephrectomy 3D CT detected 93% of renal lesions with 97% detection for renal arteries and 100% for renal veins [11]. The kidney, tumour position and landmarks were clearly defined. It is debatable whether 3D reconstruction such as this confers any extra advantage to the experienced radiologist adept with cross-sectional imaging. However, for the surgeon, 3D reconstruction produces a virtual ‘road map’ for the operation. For both studies the authors felt that 3D reconstruction helped in the overall operational approach, as well as better planning of the initial skin incision [10,11], and helped in predicting and avoiding lesions of the collecting system during NSS.

PUJ OBSTRUCTION

CT rendering can provide comprehensive images before endourological procedures to treat PUJ obstruction, including establishing the presence and relationship of crossing vessels to the renal pelvis [12]. Although CT angiography is better than 3D CT in depicting crossing vessel position, surface-rendered images display the spatial relationship of the vessel to the pelvis, and have been shown to subjectively and positively influence surgical planning [12]. CT endoscopy has also been used after treating PUJ obstruction by metallic stenting, using virtual navigation to assess stent patency [13].

STONE SURGERY

The management of a renal calculus is often dictated by the relationship of the calculus to individual pelvicalyceal anatomy. Percutaneous access and endoscopic removal of renal calculi requires the mental reconstruction of pelvicalyceal anatomy obtained from 2D images. 3D reconstruction of calyceal anatomy could help to select the most appropriate endoscopic approach. Recent work has concentrated on 3D reconstruction of the actual calculus. In a series of patients using non-contrast 3D CT, Hubert *et al.* [14] used surface-rendered images to show the complex morphology of large renal calculi. 3D reconstruction subjectively facilitated endoscopic exploration and removal of calculi. In a third of patients the authors altered the access site that would have been adopted if the corresponding axial CT and IVU images had been used.

Reconstruction of pelvicalyceal anatomy in humans has been described only once [15]. CT surface-rendered collecting systems were acquired using retrograde or intravenous contrast medium. For patients with renal calculi, rendered images provided a clear representation of the anterior and posterior direction of calyces, information that was impossible to determine using the corresponding IVU. Experimental studies on pig kidneys using 3D CT volume rendering assisted by virtual renoscopy have been promising [16]. The combination of the diagnostic accuracy of CT with 3D modelling for appreciating the location of calculus and calyceal anatomy may displace the IVU completely (Fig. 5).

THE 'SURGICAL SIMULATOR'

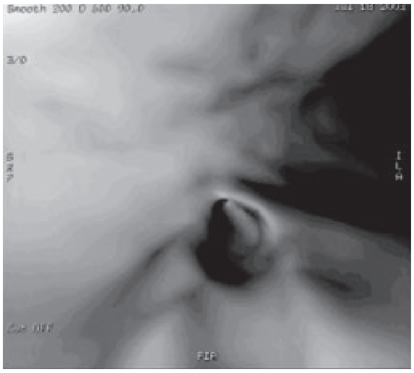
Rendered images have been manipulated to do 'mock' operations, including partial nephrectomy [11] and retroperitoneal laparoscopic nephrectomy [17]. MDCT with volume rendering using very thin reconstruction intervals has been used to produce a 3D navigator on a dedicated workstation, with the renal hilum and vessels displayed as they would be seen at laparoscopic retroperitoneal nephrectomy [17]. The 3D navigator produced excellent images, detecting all renal arteries and 96% of renal veins. The navigator was able to simulate laparoscopy and provide image angles impossible to obtain at laparoscopy [17]. This application of 3D imaging, in teaching operations and for improving a surgeon's operative skill, may become an important part of future surgical training.

CLINICAL APPLICATIONS OF 3D US

PROSTATE

3D US can produce repeatable, accurate prostate volume estimates, improved prostate cancer detection and staging, and be useful for interventional procedures [18]. Attempts to improve the sensitivity and specificity in detecting prostate cancer with 3D US alone have been mixed; isoechoic cancers on TRUS remain so on 3D TRUS. However, 3D power Doppler angiography using an intravenous ultrasound contrast agent has shown promising results. This method has exploited differences in vascular asymmetry between cancerous and noncancerous regions to increase the sensitivity and specificity. This technique obtained 85% sensitivity (80% specificity) compared with 77% sensitivity (specificity 60%) for conventional TRUS [19].

FIG. 4. CT cystoscopy; a view of the ureteric orifice.



Another advantage of 3D TRUS over conventional TRUS is that the prostate can be viewed in the reconstructed 'coronal plane' and displayed in real time simultaneously with the two standard planes. This real-time application (known as 4D) is absent in 3D CT or 3D MRI [18].

BLADDER

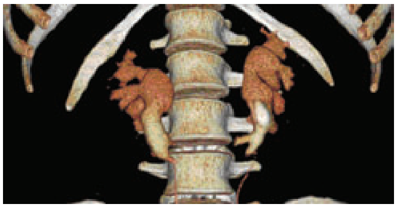
The authors' ward- and outpatient-based bladder scanners presently use 3D US techniques to measure bladder volumes. The 'BladderScan^{TM}' is a rudimentary 3D US system which uses a probe with an internal motor that rotates the transducer in 15° intervals whilst the probe is kept still over the suprapubic region. This results in 12 spatially interlocked images from which a volumetric model of the whole bladder is constructed. The instantaneous volumes calculated via this simple 3D volumetry have an accuracy of 94% with good interobserver variability [20].

RENAL

Currently, 3D US has not been exploited for the kidney, as the depth and complex ultrasound features of the kidney present difficulties for current hardware/software. This is disappointing, as 3D renal US could be used for real-time guidance and monitoring of endourological and percutaneous procedures in the operative arena.

In general, weaknesses of 3D US are related to deficiencies of conventional US, e.g. poor organ penetration related to habitus and respiratory interference. Furthermore, 3D US systems with electromagnetic positional orientation devices have to be scanned in environments lacking ferrous material, to avoid undue interference. Future 3D US systems are likely to be based on transducers which use digital processing to obtain 3D volumes in a fraction of the current time.

FIG. 5. 3D CT of the renal tract, with volume rendering, showing a 3D reconstruction using 16-slice CT with intravenous contrast medium, detailing the pelvicalyceal anatomy and a left renal stone in a horseshoe kidney.



CONCLUSION

The inherent attraction of 3D imaging for surgeons is the appreciation of spatial relationships in a way that conventional images are unable to portray. However, it is not necessary for 3D modelling to be applied to every investigation unless extra information is to be gained. Factors such as patient acceptability, tolerance, safety, convenience and cost must always be considered.

In the future it will become economically unfeasible and practically difficult for doctors to continue processing the large volumes of axial data that are currently obtained. Inevitably data will need to be displayed in a manner that is most easily accommodated by the eye, as well as adding to diagnostic and clinical value. As data acquisition techniques becomes faster and better (along with ever-increasing processing power) it is only a matter of time before 3D imaging techniques are widely used in most hospitals. Their use will further add to the extraordinary advances in medical imaging that have occurred over the past decades.

CONFLICT OF INTEREST

None declared.

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Abbreviations: **3D**, **2D**, three (two)-dimensional; **US**, ultrasonography; **MDCT**, multidetector row CT; **NSS**, nephron-sparing surgery.