

ORIGINAL ARTICLE

Real-time three-dimensional ultrasound visualization of erection and artificial coitus

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Summary

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To investigate the feasibility of imaging penile erection and coitus in real time and in three dimensions, a 'Live' three-dimensional (3-D) ultrasound system was used to acquire the volume of interest at 25 Hz from five healthy men. Water baths and gel-made artificial vaginas were devised to facilitate the 3-D scans without the probe being in direct contact with the penis. For the first volunteer scanned with the water bath alone, the penis failed to erect within 30 min. For the other four volunteers, the 'vagina' successfully initiated and maintained the erection and allowed artificial intercourse. Results have shown that the 'Live' 3-D ultrasound and minimally compressive imaging techniques together can offer an objective means for visualizing erection and coitus in spatial totality and temporal reality. They can be further developed to reveal more reliable details about the dynamic morphology, improving scientific understanding of sexual activities and clinical management of related problems.

Introduction

The exact mechanisms of penile erection remain unclear and have been under constant revision with new scientific findings. However, the basic haemodynamic morphology of penile erection is well understood. The erection is achieved sequentially as a result of increased arterial inflow, engorged cavernosal microvascular cavities and blocked venous drainage. The blockage is caused by the increased corporeal pressure which compresses the relaxed veins against the tunica. Full rigidity is accomplished by the contraction of the perineal muscles (Borowitz & Barnea, 2000). Aspects not understood include regional variations within the corpora cavernosa and potential small vessel disease, both of these cannot fully be assessed by conventional, cross-sectional ultrasound imaging of the anatomy and point-based spectral Doppler sampling of blood flow.

It is well recognized that anatomical, physiological and psychological problems can cause erectile dysfunction, which has serious consequences for lovemaking and fertility (Fabbri *et al.*, 2003; Russell & Nehra, 2003). Yet, there have been no objective means to observe the dynamic mor-

phology of penile erection and coitus in real time and in three dimensions, not to mention any observations of these activities at patients' own physical and emotional convenience. Current knowledge of the dynamic morphology, including the haemodynamic morphology mentioned above, has mainly been derived from non-physiological data obtained by autopsical, histological, interventional, and/or pharmaceutical-response observations.

Ultrasound and magnetic resonance (MR) are non-invasive imaging modalities which can be used to visualize body parts. Over the last decade, the role of MR imaging has increasingly been investigated in diagnosis of various penile diseases (Andresen *et al.*, 1998; Faix *et al.*, 2002; Hauck *et al.*, 2003; Moncada *et al.*, 2004; Scardino *et al.*, 2004). However, MR data acquisition is slow and even two-dimensional (2-D) images cannot be attained in real time. A single static three-dimensional (3-D) data set of penile anatomy and its main vessels can be acquired, but it takes several seconds to several minutes during which the penis has to be kept immobile (Pretorius *et al.*, 2001; Thiel *et al.*, 2003).

Ultrasound data can be collected more rapidly (Hampson *et al.*, 1992; Cormio *et al.*, 1998). An advanced

scanner with a high-resolution probe can obtain real-time images of penile cross-sectional anatomy and blood flow (at around cinematic rate of 25 frames/sec).

From the dynamic morphological point of view, erection is caused by changes in vasculature and musculature. Although the latter is under some voluntary nervous control, the dominant mechanism of erection is involuntary endocrino-vascular action. Appropriate erection (without medication) can only be achieved through physiological and psychological potency which allows hormones to be released at the right time and to work on the overall responding penile vasculature in the correct sequence and for an appropriate duration. Therefore, an ideal modality for imaging erection should be able to acquire anatomical and vascular information in its spatial totality (rather than just in cross sections) with real-time dynamics (the importance of this will further be discussed later), and in a comfortable scanning environment for the subject and his partner.

Ultrasound has been used for acquiring dynamic 3-D images, fundamentally by two methods (Deng, 2003b). The first one is motion-gated slice-reconstruction method. It uses an imaging plane to scan over a volume of interest to obtain serial slices. To avoid/reduce motion artefacts, the probe movement has to be synchronized with repeated body part motion. This is easier when the motion repetition is regular, such as with heartbeats or simple lip pouts (Deng *et al.*, 2000, 2002b; Deng, 2003a). However, this is not the case during erection and intercourse as the muscular dynamics and vascular kinetics are erratic.

The second dynamic 3-D method is real-time volumetric imaging. It uses an imaging volume rather than a plane to scan a volume of interest (von Ramm & Smith, 1990). As imaging volume is updated at around cinematic rate of 25 volumes/sec, many body part movements can be acquired in 3-D without motion artefacts (Deng *et al.*, 2002a; Deng, 2003a). However, it was not until recently that spatial resolution of real-time volumetric imaging has become clinically useful, thanks to progress in micro-electronics and medical graphics (Deng, 2003a; Wang *et al.*, 2003).

Another problem with conventional ultrasound scanning is deformation artefacts. It is caused by direct contact between the probe and skin, and the subsequent pressure from the probe compresses delicate soft tissue and impedes movement. To avoid this in an orofacial study, we devised various water/gel baths to mediate ultrasound transmission between the probe and target without the need for direct contact. This allows the natural shape of the lips to be retained and pouting and other oral actions to be undisturbed during scanning (Deng *et al.*, 2000; Deng, 2003a).

In this paper, we report our initial experiences in utilizing the latest generation of real-time volumetric ultrasonography – the Live 3-D system, together with purpose-built minimally compressive settings to visualize the functional anatomy of the penis during erection and coitus.

Materials and methods

Subjects

Non-invasive 3-D ultrasonographic study of the dynamic body parts was approved by the UCL Ethical Committee. Five men with no history of erectile dysfunction volunteered for this trial with informed consent. These included two completely healthy men and three men with a past history of biliary colic. The latter were otherwise normal, and had been referred to us for ultrasonographic exclusion of gallstones.

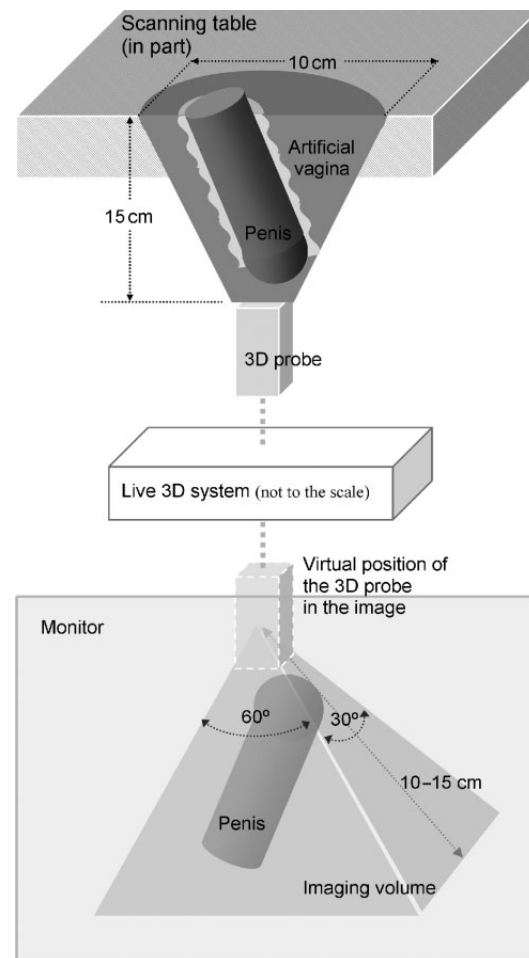


Figure 1 Diagram of the minimally compressive scanning setting and the Live 3-D imaging volume (see text for more information).

Minimally compressive scanning settings

To facilitate non-contact scanning, we first designed a water bath with an acoustic plastic wall. It was slotted into a hole on a scanning table, with its top level with the table surface. Acoustic gel was moulded into a vagina-shaped cavity and placed in the bath. This allowed the penis to be stimulated by making gentle in-out movements within the mould (Fig. 1).

Real-time 3-D system

A Live 3-D ultrasound system (Sonos 7500; Philips, Botolphell, WA, USA) was used for 3-D data acquisition and display. A 2–5 MHz broadband probe (X4 transducer) was set to run at 5 MHz to achieve the finest spatial resolution. The image depth was set to 10–15 cm. The angles of the pyramidal imaging volume were about 60° by 30° (Fig. 1). Under these settings, the system could capture around 25 volumes/sec, so that the erection and coitus were visualized in real time.

3-D data acquisition

Because data were acquired and rendered in real-time, 3-D images were displayed on the monitor at all times during the scan. In order to position the probe at an appropriate angle and set an appropriate imaging depth according to the penile position and length, the penis was kept immobile for about 5 sec when it was at rest and when it was fully erected, respectively. One to two static 3-D data sets were recorded from the resting and erect

positions. For the erect penis, a further two to four dynamic 3-D data sets were acquired when the penis was performing intercourse through the gel vagina.

3-D data analysis

The system's ability to visualize static and dynamic penile structures under minimally compressive scanning conditions was assessed qualitatively against 'known' anatomy as detailed in the Results section. Analysis was performed both during and after scanning. Post-scanning analysis was carried out on a TomTec 4D CardioView workstation (Munich, Germany), which offers more versatile controls for manipulating the data at the operator's convenience (Fig. 2).

Results

Placing the penis into the water bath without using a gel vagina, the first volunteer had difficulty in initiating erection within 30 min despite the use of visual stimuli. Inserting the penis into a gel vagina in the water bath and making gentle in-out movements, the remaining four subjects achieved grade III (full rigidity) erection in about 5 min without visual stimulation. They also maintained the erection (and performed coitus) for about 2–5 min until a short while after ejaculation.

Real-time 3-D images of the penis without deformation were successfully obtained for continuous assessment during and after the scans. When the subjects were still able to keep the penis immobile or to perform only gentle intercourse, the imaging volume could be interactively

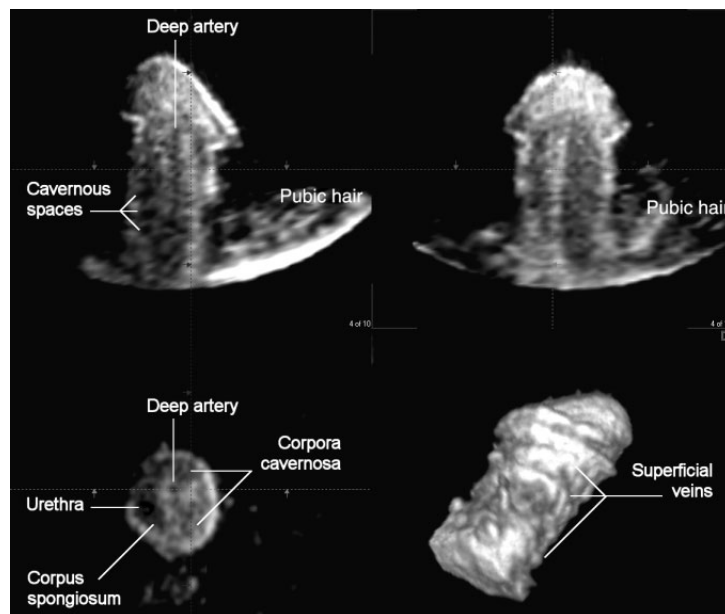


Figure 2 Dynamic 3-D imaging of penile erection. The lower right image is a 3-D surface view, not only showing the penile body and glans but also the dilated superficial veins. The remaining three images are 2-D views reformatted from the 3-D data set. Upper left, right and lower left are sagittal, transverse and coronal views, respectively. (A real-time 3-D movie is available on <http://www.medphys.ucl.ac.uk/mgi/jdeng/> following links 'Body Parts', then 'Erecting Penis'.)

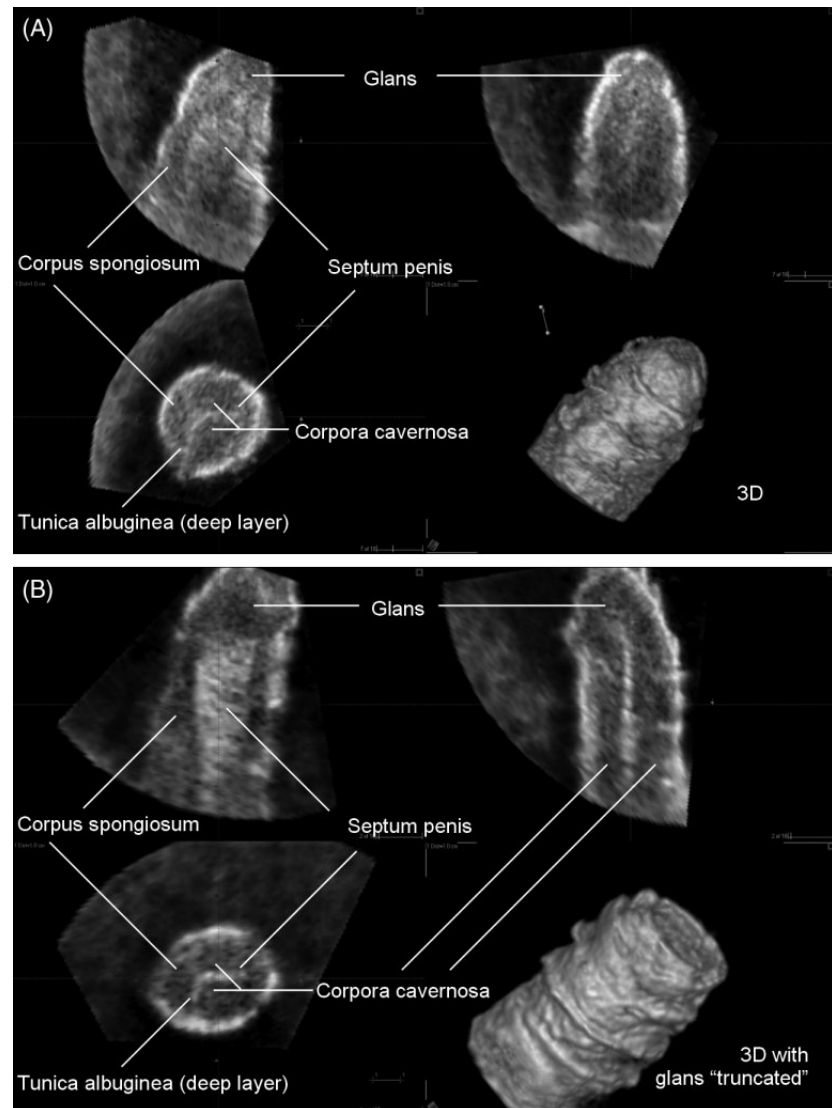


Figure 3 Penile size and intensity changes during erection – (A): just erected; (B): fully erected. Note the increased contrast between the erectile tissue and septum penis (connective tissue). This is probably due to increased blood filling in the cavernous spaces, reducing echogenicity of erectile tissue (making it appear darker).

aligned to cover almost the whole penis (Fig. 3). When the penis was fully erected or ejaculating, the movement became erratic and the imaging volume was no longer able to encompass the penis entirely (see the Internet movie link from Fig. 2), and ejaculating jets were not fully captured by 3-D acquisition.

From the last four volunteer scans, the main penile structures could be identified in both static and dynamic 3-D images during both resting and erect states (Figs 2 & 3). Corpora cavernosa and corpus spongiosum (and the urethra within the latter) were better delineated in erectile than in baseline images. The course of deep arteries and dilated superficial veins were more readily noted in erect penis images. Echo intensity in corpora cavernosa decreased from baseline to erection, with increased size and numbers of small darker areas in these structures. These findings appeared to be consistent in all the four patients.

Discussion

Using the latest ultrasound system with a matrix probe, this study has shown the feasibility of real-time 3-D visualization of penile functioning anatomy in healthy volunteers. The real-time imaging permits interactive probe positioning and imaging-depth setting in accordance with the physiological status of the penis.

The minimally compressive scanning settings have allowed the penis to perform erection and 'coitus', which would otherwise be constrained by conventional 2-D or 3-D approaches requiring direct probe contact with the penis. The gel vagina has helped to initiate and maintain erection.

Our preliminary findings seem to suggest that sonographic changes in penile arteries, cavernous spaces and veins during erection-intercourse, together with their

spatial relationships to each other and to the tunica, may all be captured by real-time volumetric imaging (Fig. 3). We speculate that the overall decrease in echo intensity and increase in the size of small dark spots in the corpora cavernosa may reflect the changes in microvasculature (i.e. indicate more blood filling individual cavernous spaces). This does not necessarily mean that the ultrasound imaging resolves all these micro-spaces, but grossly reflects the overall change in blood filling status. When displayed in a 2-D medium (on a paper sheet or computer screen), these 3-D images/movies may not look better than conventional 2-D images obtained by a state-of-the-art cross-sectional scanner. However, as the data can now be acquired in its spatial totality over time, the new techniques may enable three overall assessments: (i) analysis of temporal sequence of arterial, cavernous and venous response to psycho-physiological and/or pharmaceutical stimuli, (ii) quantification of the penile volume and volumetric change, (iii) characterization of the erectile tissues. The first two advantages will most likely improve our fundamental scientific understanding of erection mechanisms, in the long term benefiting clinical practice. The third advantage lies in the fact that the penis is a superficial structure, and acquisition will be much less affected by imaging window and body obesity. As a result of this, tissue characterization that can hardly be carried out in internal organs (say the liver) can be easily done in the penis. Additionally, because the penis was visualized in its totality, tissue characterization can be performed in 3-D, providing more meaningful information than 2-D imaging can do about the overall erectile tissue property. This may be useful for global quantification of the extent of pathological changes in such as Peyronie's disease.

Because of the difficulty recruiting unpaid healthy volunteers, the subject number of this pilot study was small. Further studies are needed to substantiate our current elaboration of our initial findings. However, due to the fact that the penis is an external organ and is less subject to individual variations in terms of ultrasound imaging conditions, the imaging settings worked out from this study should be largely applicable to a large number of volunteers/patients.

With the recent addition of 3-D colour Doppler mode to the scanner, we could image dynamic 3-D penile blood flow. A separate preliminary study by us using this technology in six patients with post-transplantation erectile dysfunction has already revealed rapid and transient vascular changes in response to sildenafil (Viagra, Pfizer, Sandwich, UK) which would be missed by conventional scanning (Chatterjee *et al.*, 2004). While standard caverject injection was so poorly tolerated by some of the patients that unphysiological results were obtained, results from all patients using

sildenafil and the 3-D approaches suggested that painful penile injection can be avoided, and more physiological information can be obtained.

However, further developments are needed to improve spatial resolution, increase imaging volume and achieve real-time 3-D blood flow imaging. With these improvements expected to be commercially available soon and with appropriate settings by radiologists, there will be no technical restriction to couples performing penile (and clitoral) scans by themselves and in private. This will provide much needed information in even better physiological conditions, assisting the integrated study of behavioural, cognitive, medical and surgical approaches to solving sexual problems.

In summary, real-time 3-D ultrasound imaging and minimally compressive scanning techniques have presented an opportunity of observing dynamic morphology of the penis never seen before in its spatial and temporal entirety. This may offer an objective means for studying normal and pathological erection and coitus.

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