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REVIEW

Toward a Highly-Detailed 3D Pelvic Model:
Approaching an Ultra-Specific Level for Surgical Simulation and Anatomical Education

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The surgical anatomy of the pelvis is highly complex. Anorectal and urogenital dysfunctions occur frequently after pelvic oncological surgery and are mainly caused by surgical damage of the autonomic nerves. A highly-detailed 3D pelvic model could increase the anatomical knowledge and form a solid basis for a surgical simulation system. Currently, pelvic surgeons still rely on the preoperative interpretation of 2D diagnostic images. With a 3D simulation system, pelvic surgeons could simulate and train different scenes to enhance their preoperative knowledge and improve surgical outcome. To substantially enrich pelvic surgery and anatomical education, such a system must provide insight into the relation between the autonomic network, the lymphatic system, and endopelvic fasciae. Besides CT and MR images, Visible Human Datasets (VHDs) are widely used for 3D modeling, due to the high degree of anatomical detail represented in the cryosectional images. However, key surgical structures cannot be fully identified using VHDs and radiologic imaging techniques alone. Several unsolved anatomical problems must be elucidated as well. Therefore, adequate analysis on a microscopic level is inevitable. The development of a comprehensive anatomical atlas of the pelvis is no straightforward task. Such an endeavor involves several anatomical and technical challenges. This article surveys all existing 3D pelvic models, focusing on the level of anatomical detail. The use of VHDs in the 3D reconstruction of a highly-detailed pelvic model and the accompanying anatomical challenges will be discussed Clin. Anat. 26:333–338, 2013. © 2012 Wiley Periodicals, Inc.

Key words: pelvis; 3D anatomical model; surgical simulation; visible human datasets; autonomic nerves; endopelvic fasciae

INTRODUCTION

The surgical anatomy of the pelvis is highly complex because of the funnel-shape and the intricate anatomical arrangement. Nowadays, pelvic oncological surgery emphasizes radical resection of the tumor within free circumferential margins as well as postoperative functional outcome. The complex

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anatomy plays an important role in both outcomes. An incomplete mesorectal resection was found in 79% of the cases by pathological evaluation, showing a marked variability in the surgical dissection plane (Leonard et al., 2010). Anorectal and urogenital dysfunctions occur frequently and are caused mainly by surgical damage to the autonomic nerves (Wallner et al., 2008; Lange et al., 2009). Hence, knowledge of the pelvic anatomy must be improved.

3D anatomical modeling is of increasing interest in clinical medicine. Besides CT and MR images, Visible Human Datasets (VHDs) are widely used in 3D reconstructions due to their high degree of detail. Surgical simulation systems can be developed based upon a 3D model. The anatomical completeness of such a model strongly influences the clinical usefulness of simulation systems. Currently, these are most important in neurosurgery (Beriault et al., 2011; Robinson et al., 2011), hepatic surgery (Reitinger et al., 2006; Debarba et al., 2010), and orthopedic surgery (Heng et al., 2006; Cimerman and Kristan, 2007). However, pelvic surgeons still rely on the interpretation of 2D preoperative diagnostic images. A highly-detailed 3D pelvic model could increase the anatomical knowledge and form a solid basis for a pelvic surgical simulation system. In this way, pelvic surgeons can simulate and train different surgical scenes to enhance their preoperative knowledge and improve oncological and functional outcome.

This raises the question whether proper 3D pelvic models have been developed in order to build an effective simulation system that visualizes key surgical structures. Do the currently available VHDs provide enough level of anatomical detail? In this article, all existing 3D pelvic models will be surveyed, focusing on the level of anatomical detail. The use of VHDs in the 3D reconstruction of a highly-detailed pelvic model will be discussed. Furthermore, we discuss the anatomical challenges in creating a comprehensive atlas and we conclude with an outlook on the future of the development of a highly-detailed pelvic model.

3D PELVIC MODELS

Up to now, 17 3D pelvic models have been created. A complete overview of the anatomical structures included in these models can be explored online: http://www.caskanatomy.info/research. The most representative models are depicted in this section.

Stanford University recognized as first the importance of including more anatomical detail in 3D reconstructions (Heinrichs et al., 2004). Their surgical simulation system called ‘‘LUCY’’ contained vascular, neural, lymphatic, and fascial structures, though this was not further specified. Bajka et al. (2004) focused on creating a simulation system as well and integrated quite sufficiently blood vessels. In contrast, nerves, lymphatics, and fasciae were missing. A virtual model was created for interactive education by Sergowich et al. (2010). Despite clear convenience of integrating virtual reality technologies with anatomical data, the pelvic anatomy was severely incomplete. Holubar et al. (2009) developed a virtual simulation system, but the lack of surgically important structures rendered it unsuitable for accurate simulation. This was affirmed by a pilot study of its usability and perceived effectiveness. Fifty percent of the participants felt the system needed a higher level of anatomical detail and specifically requested inclusion of, e.g. Denonvilliers’ and Waldeyers fascia (Hassinger et al., 2010).

VISIBLE HUMAN DATASETS

The first VHD was released in the mid-nineties (Ackerman, 1999) and its success initiated the development of additional VHDs. All the features of these datasets are accessible online at: http://www.caskanatomy.info/research. Segmentation of the 2D images is the crucial step in creating a 3D model. That is organizing the image content into semantically related anatomical groups and associating similar anatomical features by anatomical labeling. The quality and usefulness of the VHDs is determined by the cross-sectional interval, spatial resolution, color depth, and cadaveric preservation methods.

We also developed a novel VHD of a female pelvis. All images were of high quality due to a spatial resolution of 3,040 × 1,961 pixels and a cross-sectional interval of 75 μm, which is an improvement compared to the previous developed VHDs. We intended to evaluate the possibility to create a highly-detailed 3D model based upon segmentation of merely cryosectional images. Information regarding the development of the so-called University Medical Center Utrecht Pelvic dataset (UMCU pelvic dataset) can be accessed online at: http://www.caskanatomy.info/research. We questioned whether it was possible to segment the complete pelvic vasculature, autonomic nerves, peri-rectal fasciae, and lymph nodes.

All important branches of the internal and external iliac vessels were identifiable. Difficulties were observed by precise branching patterning of venous plexuses surrounding the bladder, vagina, and uterus, caused by the postmortem expanding of these plexuses. One can question though, if this would be a crucial anatomical component for a pelvic surgical planning system (see Fig. 1).

The identification of nerves was limited to a certain size. The sacral roots, obturator nerve, and femoral nerve were easy to recognize, yet autonomic nerves were not traceable at all. Peri-rectal fasciae were quite well visible. Nonetheless, exact arrangement was not examinable at the level of Denonvilliers’ fascia and its lateral continuation. Thereby, determination of visceral and parietal layers was not possible and there were no relationships visible between fasciae and autonomic nerves (see Fig. 2).

Moreover, lymph nodes were seen around the iliac vessels, obturator artery, and within the mesorectum. This is in concordance with the findings of Qatarneh et al. who identified about 60 solid lymph nodes in these areas (Qatarneh et al., 2006). However, no lymphatic pathways were visible.

Hence, usage of solely VHDs is not enough to build a highly-detailed anatomical atlas of the pelvis, because of the inability to identify and segment au-

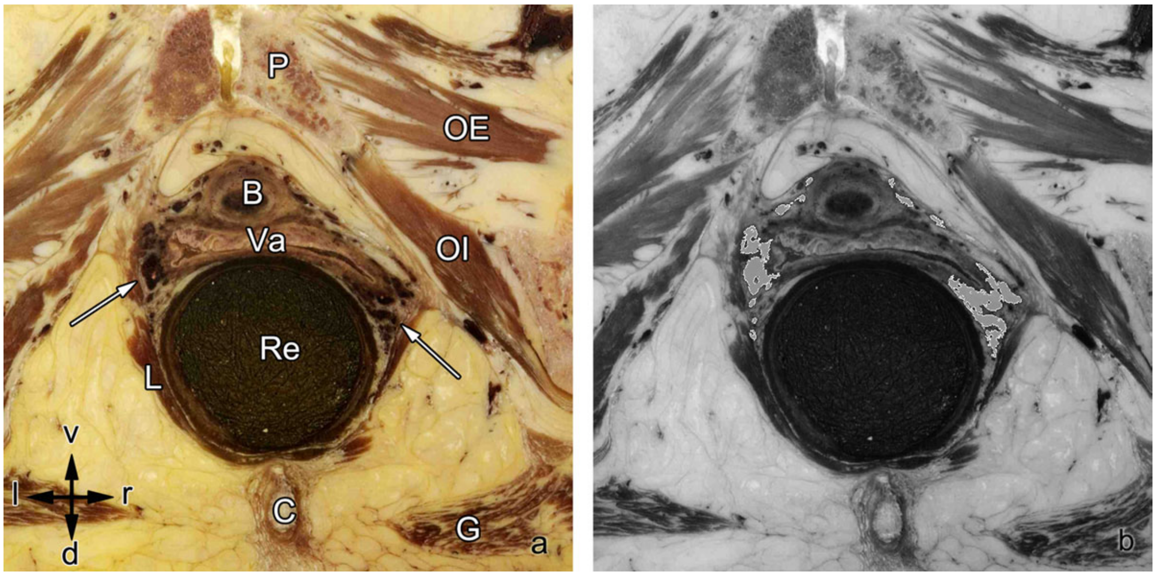

Fig. 1. Complex vascular arrangement surrounding the bladder, vagina, and rectum. Precise branching patterning of vasculature surrounding the pelvic organs is difficult because of postmortem expansion of the venous plexus (arrows, **a**). (**b**) Comprises an impression of segmentation of this plexus and shows the inability to define small branches. B: bladder, Va: vagina, Re: rectum, P: pubic bone, OE: obturator external muscle, OI: obturator internal muscle, L: levator ani muscle, C: coccyx, G: gluteal maximus muscle. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

tonomic nerves, fasciae, and lymphatic structures in cryosectional images.

MAJOR PROBLEMS IN DEVELOPING AN ANATOMICAL PELVIC ATLAS

The pelvic autonomic network has been studied intensively. It is questionable whether all minuscule neural branches should be included in a 3D pelvic model, as surgeons will not be able to preserve every branch. Multiple intra-plexus and bilateral plexus connections exist, which may warrant sufficient autonomic function after unilateral surgical damage (Kinugasa et al., 2006). The clinical value of the 3D reconstruction of these nerves lies in the visualization of surgically important vulnerable tracts, such as the inferior hypogastric plexus at the level of the middle rectal artery or sacrouterine ligament.

Moreover, lack of precise anatomical knowledge makes it impossible to reconstruct an accurate anatomical atlas. For example, the relation between endopelvic fasciae and autonomic nerves is of crucial importance as most damage occurs because of dissection in the wrong surgical plane. This anatomical relation has been frequently studied, but it remains still under great debate. Although there is absolute agreement that the mesorectum is surrounded by a visceral fascia, there is no consensus about the fasciae anterior, posterior, and lateral to the rectum and numerous studies have been conducted to elucidate this confusion (Lindsey et al., 2005; Kinugasa et al., 2007; Zhai et al., 2009; Zhang et al., 2010).

Furthermore, the uptake of the lateral rectal ligaments in a 3D reconstruction can be disputed. Since Miles proposed abdominoperineal excision as radical surgery for rectal cancer (Miles, 1971), the identification by ‘‘hooking them on the finger’’ has been accepted by many surgeons. On the other hand, Heald did not mention the lateral rectal ligaments in his description of total mesorectal excision (Heald and Ryall, 1982). Some clinical studies recognize the existence of the lateral rectal ligaments (Wang et al., 2010), though many anatomical studies were not able to locate the lateral ligaments and defined them as a surgical artifact created by traction of the rectum (Takahashi et al., 2000).

Massive lymph node involvement is known as a major risk factor for recurrent disease in rectal carcinoma (Kusters et al., 2010). Uptake of the lymphatic system would give perfect insight into its relation with nerves and could help to determine whether nerve-sparing surgery might be possible.

RECONSTRUCTION POSSIBILITIES

As the currently available VHDs are not sufficient in developing a highly-detailed 3D pelvic model containing key surgical structures, other techniques have to be applied to fill up missing anatomical data. Graphic modeling can be used to complete missing parts; however it requires enough input data. Ball-shaped markers of variable diameter can be placed onto blind ends on cross-sectional images and extrapolated to fill missing parts (Hohne et al., 2001; Pflesser et al., 2001). Stereoscopically drawing of missing structures may be an option as well (Shin et al., 2011). Nevertheless, the lamellate arrangement of nerve plexuses and layer-like composition of fasciae will neither allow tube-like reconstruction nor stereoscopically drawing.

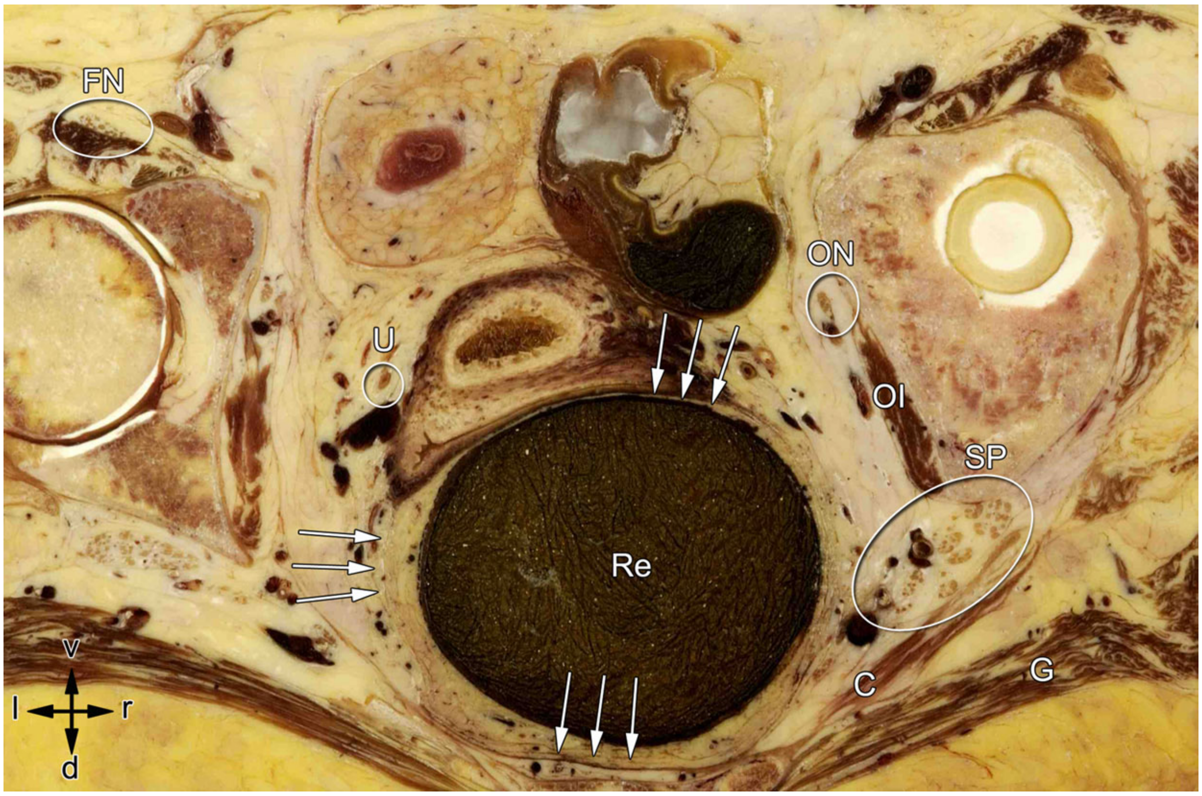

Fig. 2. Difficulties in the identification of pelvic autonomic nerves and peri-rectal fascia sheaths. The sacral plexus, femoral nerve and obturator nerve are well detectable, though no pelvic autonomic nerves are identifiable surrounding the rectum. Posterior to the rectum, the fascia sheaths are well-defined; however no differentiation between visceral and parietal layers can be made (lower arrows). The fascia of Denonvilliers should be situated between the dorsal wall of the vagina and the ventral rectal wall (upper arrows) but cannot be identified separately. Its lateral continuation is unclear as well (left arrows). Re: rectum, OI: obturator internal muscle, G: gluteal maximus muscle, C: coccygeal muscle, U: ureter, SP: sacral plexus, FN: femoral nerve, ON: obturator nerve. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Microscopically, the autonomic nerves are well detectable by immunohistochemistry. Recent studies have revealed the composition of parasympathetic, sympathetic, and sensory fibers within the autonomic network and three-dimensionally reconstructed their findings (Alsaid et al., 2009, 2011a,b).

The vasculature might be reconstructed by using several novel technologies. Ding et al. (2008) established a 3D model of the pelvic vasculature by fresh cadaveric perfusion with a carboxymethyl cellulose/lead oxide mixture and subjection to CT scanning. Another possibility is to detect vessels by visualizing fluorescently labeled microspheres with an imaging cryomicrotome (van Horssen et al., 2010). Incorporation of all anatomical details may lead to superfluous information which can easily end up in a confusing overload. However, key surgical structures must be separately identified in high-resolution microscopic studies and combined in a general model.

DISCUSSION

None of the existing 3D pelvic models is suitable for a surgical simulation system due to the lack of essential anatomical details. Although some models are primarily designed for educational purposes, high-quality educational training tools should contain specific anatomical details as well. The lack of image contrast in the current VHDs greatly complicates the segmentation of autonomic nerves and fasciae. Specific staining should distinguish between similar colors, such as ligaments, connective tissue, and nerves. Usage of oblique light might reveal more detail compared to perpendicular light as well.

Current technologic advances enable preoperative anatomical analysis of patients with high accuracy of radiologically visible structures. By using multidetector CT imaging lymph nodes and coronary arteries are sufficiently detectable (Nikolaou et al., 2004; Silverman, 2005; Cezlan et al., 2012). MR lymphangiography or lymphscintigraphy can be used to detect lymphatic pathways (Notohamiprodjo et al., 2012). Recently, the rami orbitales in the pterygopalatine fossa have been visualized using the high-field 7 Tesla MRI (Oomen et al., 2012). In spite of the potential to radiologically visualize smaller structures, it remains still impossible to adequately image the autonomic nerves, fasciae, and their mutual relation. In addition, the lack of knowledge about specific anatomical components thwarts their identification. The ongoing discussion about Denonvillier's fascia, peri-rectal fasciae, and their relation with autonomic nerves firstly demands microscopic clarification and uniform acceptance.

Daily clinical use of a highly-detailed 3D pelvic model for surgical simulation depends strongly on the inclusion of key surgical structures. Fasciae form the anatomical landmarks during surgery, oncologic outcome depends on adequate removal of lymphatic tissue, and functional outcome demands nerve preservation. These specific anatomical details cannot be extracted from the current VHDs and hence other techniques should be applied such as microscopic analysis.

The development of a 3D model based upon multiple image modalities requires a software system that is able to effectively combine different data types. Recently, new software was developed that integrates heterogeneous anatomical data in one unified model. This can be used to effectively combine segmentation results from VHDs with microscopic data. Furthermore, it was possible to map a random pelvic CT scan successfully onto digital images from a pelvic dataset. As a proof of concept, the sciatic nerve was extracted from the pelvic dataset segmentations and separately mapped onto the CT scan (Smit et al., 2012). These results are promising especially regarding the possibility to develop a patient-specific model. This will be simultaneously a huge technical challenge. The predictive power of a future 3D pelvic model depends on the ability to visualize patient-specific information based upon a highly-detailed basic anatomical model.

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