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MALE PELVIC ANATOMY RECONSTRUCTED FROM THE VISIBLE HUMAN DATA SET

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ABSTRACT

Purpose: To improve understanding of the male pelvic anatomy pertinent to urological surgery we performed computer generated, 3-dimensional reconstruction of the male pelvis from the Visible Human data set.

Materials and Methods: A total of 18 discrete anatomical structures, including the prostate, bladder, urethra, rectum and pelvic musculature, was segmented from the Visible Human cross-sectional data obtained from the National Library of Medicine. Using high speed computing and rendering software, 3-dimensional models of each structure were generated and assembled into composite figures.

Results: These reconstructions offer a revised view of pelvic anatomy as it has been traditionally depicted. The lateral surfaces of the levator ani muscle are oriented vertically in the pelvis and directly applied to the entire lateral surface of the prostate. The bladder rests primarily anterior to the prostate rather than directly above it, as has been commonly depicted. In the cross-sectional data and reconstructions the trigone and anterior fibromuscular stroma of the prostate appear as a single unit in continuity, which may have functional implications for understanding the mechanisms of continence at the bladder neck. The striated urethral sphincter appears circular with abundant tissue posteriorly. This sphincteric muscle has greater length anteriorly than posteriorly.

Conclusions: These 3-dimensional reconstructions provide unique insights into male pelvic anatomy. They are a useful teaching tool for investigation and virtual reality modeling of the male pelvis.

KEY WORDS: prostate, pelvis, anatomy

A thorough understanding of periprostatic anatomy is critical to the successful performance of urological pelvic surgery. Of particular importance are the structures essential to male urinary continence, namely the preprostatic sphincter region, prostate, striated urethral sphincter and levator ani muscle. Unfortunately understanding and depicting the spatial relationships of the pelvic organs and surrounding musculature present a formidable challenge. The fixation of cadaveric specimens distorts the natural contour of muscles and may vastly alter the relationships between structures in vivo. Dissection of complex areas, such as the urogenital diaphragm, necessitates the destruction of adjacent structures and loss of normal anatomical landmarks essential to spatial orientation. As a result, a number of inaccuracies have been introduced and propagated in illustrations of pelvic anatomy. For example, the urogenital diaphragm and striated urethral sphincter are often depicted as a flat sheet of muscle sandwiched between inferior and superior fasciae. Recent anatomical studies provide evidence that the striated sphincter more closely resembles a vertically oriented cylinder of muscle extending from the apex of the prostate to the bulbous urethra.[1–3] However, in these studies it was difficult to place the striated sphincter in the context of other important pelvic structures.

Two important advances present an opportunity for improved depiction, teaching and understanding of pelvic anatomy. High speed computers with 3-dimensional (D) graphic capabilities allow sophisticated reconstruction and manipulation of complex objects. In addition, accurate digital cross-sectional anatomical data have become available through the Visible Human Project under the direction of the National Library of Medicine.[4] In this large data set, encompassing approximately 15 gigabytes of computer memory, digitized cross-sectional computerized tomography, magnetic resonance imaging and tissue images have been collected at 1 mm. intervals. To produce an accurate rendering of the pelvic and periprostatic anatomy relevant to urinary continence in men we used the Visible Human data set to reconstruct the bony pelvis, levator ani musculature, bladder, prostate, striated urethral sphincter, perineal membrane, rectum, rectourethralis muscle and deep transverse perineal muscles.

MATERIALS AND METHODS

We used exabyte tapes of pelvic and abdominal images of the male Visible Human data set, which was derived from a healthy 39-year-old man executed by lethal injection.[4] The subject had no known pelvic or urological diseases aside from an absent right testis. For the reconstructions 132 consecutive pelvic tissue images (numbers 1,859 to 1,962) were used. To facilitate image processing cross-sectional image files were decreased from 2,048 × 1,216 to 1,440 × 1,080 pixels by cropping out the upper extremities and removing the blue gelatin background using a Macintosh Quadra800AV† computer and DeBabelizer software 1.6.5‡.

Images were imported into Adobe Photoshop§ 3.0 software

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for segmentation of 18 individual anatomical structures, including the levator ani, striated muscle of the external urethral sphincter, smooth muscle of the external sphincter, rectourethralis muscle, deep transverse perineal muscle, superficial transverse perineal muscle, bulbospongiosus muscle, ischiocavernosus muscles, rectum, ureters, bladder, bladder trigone, prostate glandular tissue, anterior fibromuscular stroma of the prostate, ejaculatory ducts, urethra, perineal membrane and perineal body. In segmentation a Brezier curve was manually traced around the outer border of each structure. Segmentation of the bladder neck, anterior fibromuscular stroma of the prostate, intrinsic smooth muscle of the external urethral sphincter and the striated urethral sphincter was confirmed by examination of hematoxylin and eosin stained histological sections of whole mounted prostates and the external urethral sphincter.

Nonuniform rational B-spline contours were generated from the Brezier curves using EAI I-Curve* software and exported to VisModel ATD* software on an IndyR5000† computer. For each anatomical structure a portion of the nonuniform rational B-spline contours was stacked and 3-D wire frame images were generated by connecting adjacent cross-sections. Using EAI Surf* software redundant contours were eliminated and a smooth surface was applied to each set of contours. Surfaced pieces of each anatomical structure were assembled into complete 3-D anatomical structures using VisModel ATD software. A unique material was applied to the surface of each anatomical structure.

Several composite 3-D anatomical models were generated by assembling individual anatomical structures. Each anatomical structure was modeled with information regarding its location and orientation in space. Therefore, composite figures were automatically assembled that maintained the normal orientation and anatomical relationships between structures. The graphics platform allows real-time 360-degree rotation and changes in model for in-depth study of the anatomical structures. Representative still frame images from these models were selected for the current study.

RESULTS

Since the cadaveric specimen was frozen in blue liquid gel to −70C shortly after death, there was excellent preservation of the anatomical structures with little distortion. Cross-sectional images of the tissues offer outstanding resolution and easy distinction of adjacent muscles, fascial planes, glandular structures, viscera and smooth muscle.

Levator ani. Reconstruction of the levator ani revealed several features not appreciated in conventional depictions of this muscle group. Viewed anteriorly the levator ani plate of musculature has a near vertical orientation with 2 small horizontal wings posteriorly at the upper limit of the muscle (fig. 1, *A* and *C*). These horizontal plates appear to be the coccygeus muscle, although individual components of the levator ani were not distinguished in the cross-sections or reconstructions. Anteriorly the 2 sides of levator ani arise separately from the pubis and, thus, the prostate is visible through the transparent pubes (fig. 1, *A*). A lateral view of this muscle reveals its posteriorly directed funnel shape as it surrounds the rectum (fig. 1, *B*). The top most posterior part of the levator ani joins the tip of the sacrum (not shown). Viewed from below the anterior portion of the levator ani forms the U-shaped urogenital hiatus, which brackets the striated urethral sphincter (fig. 1, *C*).

The levator ani is applied to nearly the entire lateral surface of the prostate with no intervening fat (fig. 2, *A*). Although it appears quite thin in its cephalad portions, it thickens considerably at its bottom edge, where it surrounds the urogenital hiatus (fig. 1, *C*). At the hiatus it is in immediate contact with the striated urethral sphincter. The urogenital hiatus of the levator ani lies at a somewhat oblique angle and comes in direct contact with the perineal membrane-urogenital diaphragm only at the perineal body at the posterior edge of the perineal membrane (fig. 2, *B*). Thus, as it fuses behind the striated sphincter at the perineal body, it forms a sling around the striated sphincter that extends from the pubic rami to the perineal body.

Bladder neck and prostatic urethra. A lateral view of the pelvic viscera demonstrates that, when relatively empty, the bladder lies almost entirely anterior to the prostate (fig. 2, *B*). The bladder neck does not rest in the horizontal plane but is tilted 45 degrees to face anteriorly. The bladder narrows at the apex, which attaches to the anterior abdominal wall and rests in the horizontal plane. Even in a relatively empty state the bladder appears to arise slightly out of the true pelvis (fig. 1, *A* and *B*).

In the fresh tissue cross sections the dense whitish muscle of the bladder trigone is clearly discernible from the surrounding pinkish-brown detrusor smooth muscle (not shown). Proceeding inferiorly from the superior margin, the trigone narrows to a waist below the ureteral orifices, then broadens and thickens posterior to the bladder at the junction of the bladder and prostate (fig. 3, *A* and *C*). At the bladder neck this whitish muscle migrates anterior to the urethra and continues down the front of the prostate as the anterior fibromuscular stroma (fig. 3, *B*). Grossly the trigone and anterior fibromuscular stroma of the prostate appear to be continuous. There is no evidence of a prepros-

* Silicon Graphics, Inc., Mountain View, California.
† Engineering Animation, Inc., Ames, Iowa.

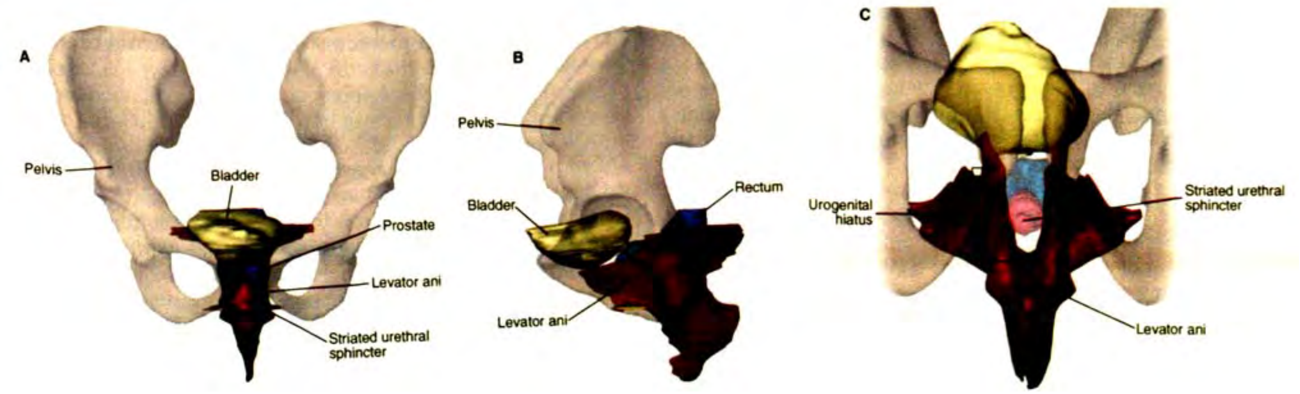

FIG. 1. *A*, anterior view of innominate bones with levator ani, pelvic viscera and perineal membrane in situ. Note near vertical orientation of lateral walls of levator ani and horizontal wings at its posterior superior aspect. *B*, lateral view of levator ani, pelvic diaphragm and pelvic viscera in anatomical position. Posterosuperior aspect of levator ani joins tip of sacrum (not shown). *C*, view of levator ani from below shows urogenital hiatus and relationship to striated urethral sphincter. Perineal body and related structures are not shown.

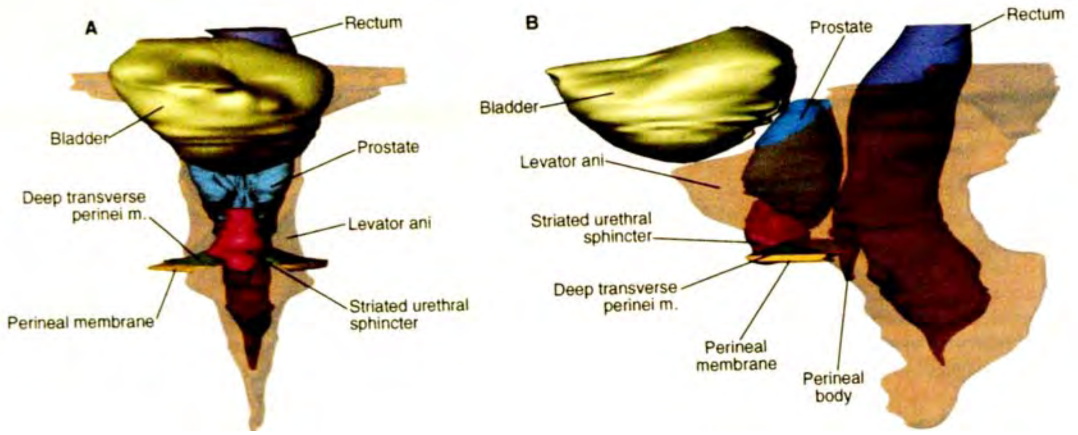

FIG. 2. *A*, anterior view of pelvic viscera and urogenital diaphragm with levator ani rendered transparent. Levator ani is applied directly to almost entire lateral surface of prostate and to lateral surface of striated urethral sphincter. Levator ani thickens at its inferior border (urogenital hiatus) near striated urethral sphincter. *B*, urogenital hiatus extends from pubis to perineal body. Note that hiatus meets perineal membrane only along its posterior border and anterior aspect of striated sphincter is visible emerging below levator ani. *perinei m.*, perineal muscle.

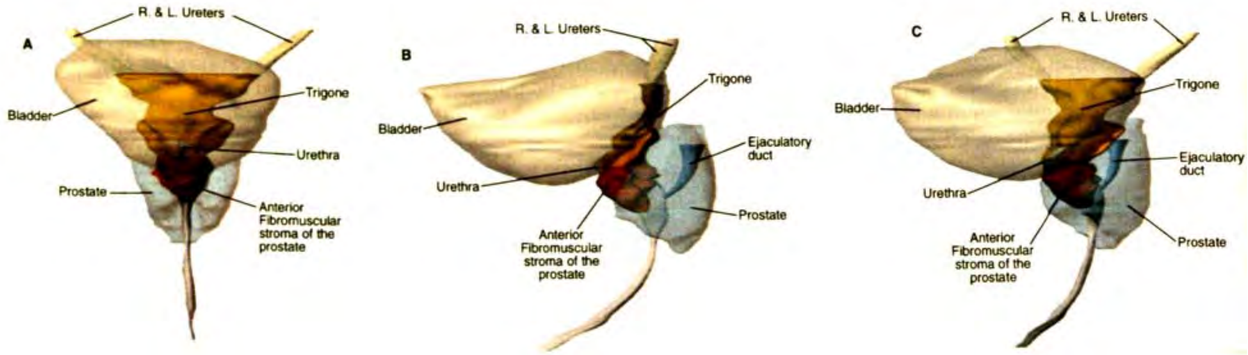

FIG. 3. *A*, anterior view reveals that trigone narrows below ureteral orifices and widens posterior to bladder neck. Trigone is continuous with anterior fibromuscular stroma of prostate. *R.*, right. *L.*, left. *B*, lateral view of trigonal anterior fibromuscular stroma of prostate shows that these structures are in continuity. Trigone thickens posterior to bladder neck and joins fibromuscular stroma anterior to prostate. *C*, oblique view of trigonal anterior fibromuscular stroma complex.

tatic sphincter extending down the prostatic urethra, since little smooth muscle was noted in the posterior wall of the prostatic urethra in the Visible Human data set or in the whole mount prostate specimens.

External urethral sphincter. The anterior wall of the striated urethral sphincter appears to be twice the length of the posterior wall and it invests the whole apex of the prostate. The posterior wall is quite thick and it appears to be primarily striated muscle in the gross tissue cross sections. In this specimen venous tissue fills the gap between the posterior wall of the striated sphincter, prostate apex, deep transverse perineal muscles and rectum (fig. 2, *B*). The striated urethral sphincter rests on top of the perineal membrane except anteriorly, where the dorsal venous complex traverses a gap in the anterior portion of the perineal membrane (fig. 4, *A*). At this point the muscle is in contact with fibers of the bulbospongiosus muscle (not shown).

A clearly discernible layer of tissue between the urethral mucosa and striated urethral sphincter is evident in the gross tissue cross sections. Microscopic examination of this region in 3 whole mount specimens revealed that this tissue corresponds to the intrinsic smooth muscle of the urethra. This smooth muscle begins immediately after the disappearance of the anterior fibromuscular stroma of the prostate and it is clearly differentiated from it in the tissue cross sections. In contrast to the anterior fibromuscular stroma of the prostate, this smooth muscle layer completely encircles the urethra. This smooth muscle sphincter begins above the striated sphincter and extends throughout its length, gradually thinning distally (fig. 4). The smooth muscle layer cannot be visualized in the most distal portion of the external urethral sphincter.

DISCUSSION

Pelvic reconstructions generated from the Visible Human data set provide several important modifications to previous descriptions of male pelvic anatomy. In the past surprisingly little attention has been given to the true contour of the levator ani muscle group. The levator ani is commonly depicted as a flattened bowl-shaped sheet of muscle that fills the pelvic outlet.[5] Reconstructions from the Visible Human data show that this muscle lies in a near vertical parasagittal plane extending from the pubis to the tip of the sacrum in men. The levator ani is quite thin throughout most of its extent but it becomes considerably thickened at the lower edge of the urogenital hiatus, where it forms a sling of muscle extending from the pubis to the perineal body posterior to the

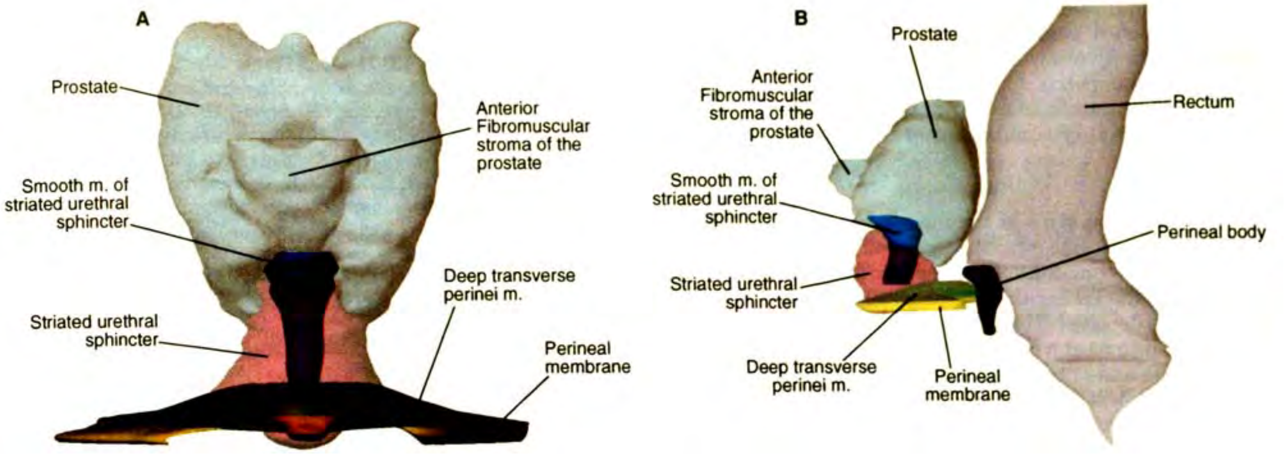

FIG. 4. *A*, anterior view of external urethral sphincter and prostate with striated component rendered transparent to reveal smooth muscle tapering distally. *m.*, muscle. *perinei*, perineal. *B*, lateral view demonstrates that anterior wall of external urethral sphincter appears twice length of posterior wall, although both are of comparable thickness. Cross-sectional view reveals that open space between posterior wall of striated urethral sphincter and rectum was filled with veins (not shown).

striated urethral sphincter. Therefore, contracting these muscles pulls the striated sphincter anterior and cephalad to force the urethral lumen closed. While the striated sphincter consists of predominantly type I slow twitch fibers, the levator ani muscles have abundant type II fast twitch as well as slow twitch fibers.[6] It is likely that contraction of this thickened levator sling at the urogenital hiatus is an important contribution to urinary continence during sudden increases in intra-abdominal pressure.

The bladder is commonly depicted as resting directly on top of the prostate with the bladder neck in the horizontal plane.[7] In our study anatomical reconstructions suggest that the bladder primarily rests anterior to the prostate with its axis at a right angle to that of the prostate. The plane of the bladder neck is directed anteriorly at a 45-degree angle and it is positioned at the meeting point of the bladder and prostatic axes. The trigone-anterior fibromuscular stroma of the prostate form what appears to be a continuous structure of smooth muscle in the plane between the bladder and prostate. To our knowledge the continuity of these structures has not been previously appreciated and our finding suggests that they may act as a single functional unit for generating continence at the male bladder neck. Urinary continence at the bladder neck had previously been attributed to the preprostatic sphincter, a cone of smooth muscle that reportedly extends from the bladder neck down the prostatic urethra to the verumontanum.[8] We found no evidence of such a preprostatic sphincter in the Visible Human data set or in the whole mount histological sections of prostate. Indeed, below the bladder neck we observed little smooth muscle in the posterior urethral wall. Sphincteric function at the bladder neck has also been attributed to opposing loops of detrusor muscle that pull the bladder neck closed as they contract. This mechanism was disputed by Tanagho and Smith, who found no structural evidence for these detrusor loops.[9] The digital tissue images available from the Visible Human data set do not allow sufficient resolution to determine the detrusor fiber mechanism. It is possible that the analog images from this data set, which are due to be released in the near future, may have sufficient resolution for reconstructing this region.

From our current study it appears that the trigone and anterior fibromuscular stroma form a single functional unit that may be important for maintaining urinary continence at the bladder neck. This new view of the structure of the bladder neck may explain why attempts to preserve the bladder neck and, thereby, improve continence at radical prostatectomy have met with disappointing results.[10] It is likely that removal of the prostate and anterior fibromuscular stroma destroys the anterior half of the continence mechanism at the bladder neck.

The striated urethral sphincter extends from the perineal membrane to the apex of the prostate. Myers reported that the posterior wall of the sphincter is thinner than the anterior wall.[2] In the reconstructed images the anterior and posterior walls of the striated sphincter appear to be of comparable thickness (fig. 4, *B*). As noted previously, the length of the striated sphincter is greater anteriorly, where it extends up to the anterior fibromuscular stroma of the prostate.[1–3] Oelrich reported that the decreased posterior length of the striated urethral sphincter is likely due to atrophy and replacement of posterior muscle fibers as glandular prostate tissue grows from the posterolateral urethral wall.[1] Myers et al noted that prostatic shape, determined by the degree of anterior and posterior growth of the prostatic glandular tissue, affects the length and shape of the striated sphincter.[11] Reconstructions of the Visible Human specimen confirm these observations. Since the preservation of continence after radical prostatectomy correlates with functional urethral (sphincteric) length, modifications to the apical dissection of the prostate to preserve maximum sphincteric length may improve urinary continence.[12]

The importance of the urethral smooth muscle at the level of the striated sphincter for urinary continence is currently unknown. In the Visible Human gross tissue sections this muscle is clearly distinguishable from the anterior fibromuscular stroma of the prostate in color and shape, since it completely encircles the urethra in the distal prostate. The thickest portion of this muscle is within the prostate proper and it would be impossible to preserve it at radical prostatectomy while providing adequate cancer control. The smooth muscle component of the external sphincter continues to encircle the urethra throughout its length and it becomes more attenuated distally. This portion can be preserved at radical prostatectomy and it may contribute to urinary control after this procedure.

Pelvic reconstructions from the Visible Human data set have improved our understanding and depiction of male pelvic anatomy, and they may be particularly useful for teaching pelvic anatomy. Further insight into the relationship of these pelvic structures can be gained through rotation of these 3-D images in computer space. While rotation may be done in real time using many workstation platforms, few students or teachers of anatomy have access to this technology. We have begun to develop 3-D models that simulate real-time manipulation in computer space using Quicktime VR† software on a personal computer. Future advances in hardware and software will allow students to perform virtual dissection of the pelvis to strengthen their knowledge of anatomy. Ultimately reconstructions may serve as models used in virtual reality simulations of urological procedures.

CONCLUSIONS

The 3-D reconstructions of the male pelvis from the Visible Human data set provide unique insights into male pelvic anatomy. The levator ani muscles are oriented vertically in the parasagittal plane rather than horizontally, as they have traditionally been depicted. The bladder lies mainly anterior to the prostate with its axis at a right angle to that of the prostate. The bladder trigone and anterior fibromuscular stroma of the prostate appear to form a single functional unit, which may be responsible for continence at the bladder neck. In addition, the striated urethral sphincter has its greatest length in the anterior wall with comparable thickness in its anterior and posterior walls. These models serve as useful tools for the teaching and investigation of male pelvic anatomy.

Exabyte tapes of pelvic and abdominal images of the male Visible Human data set and a licensing agreement to J. D. B. for their use were obtained from the National Library of Medicine, National Institutes of Health, Washington, D. C. Hematoxylin and eosin stained histological sections of whole mounted prostates and the external urethral sphincter were provided by Drs. Jonathan I. Epstein and Arthur L. Burnett, respectively, Johns Hopkins Hospital, Baltimore, Maryland. Drs. Patrick Walsh, Michael Sellberg and Alan Partin provided insights and support, and a critical reading of the manuscript. Figures were provided by Engineering Animation, Inc.

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