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SPECIAL SECTION: UROTHELIAL DISEASE

The application of cinematic rendering to CT evaluation of upper tract urothelial tumors: principles and practice

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Abstract

Upper tract urothelial carcinoma (UTUC) is a relatively uncommon but aggressive genitourinary malignancy for which multi-phase contrast-enhanced computed tomography (CT) plays an important role in evaluation and staging. 3D imaging with maximum intensity projection (MIP) and volume-rendered (VR) images has been described as a useful means of evaluating UTUC. In this study, we describe the technique of a novel 3D methodology known as cinematic rendering (CR) and provide clinical examples of UTUC visualized with CR. CR utilizes a complex universal lighting model in order to create photorealistic images with improved detail and depth in comparison to MIP or VR images. In the case of UTUC, CR can be used in different contrast phases to show abnormally thickened and enhancing urothelium or filling defects in the renal collecting system or ureters in the excretory phase. CR images can also be manipulated in order to generate translucent views of the upper urinary tract in order to add conspicuity to intraluminal findings.

Keywords UTUC · 3D · Computed tomography · CR

Introduction

Urothelial carcinoma is the second most common genitourinary malignancy with approximately 150,000 new cases in the United States in 2018 [1]. Although upper tract urothelial carcinoma (UTUC, i.e., disease affecting the renal calyces, renal pelvis, or ureters) is a relatively rare condition compared to urothelial carcinoma of the bladder [2], it tends to be a more aggressive entity with a higher rate of invasive and metastatic cases at presentation [3]. Thus, the development of imaging approaches that might improve the diagnostic yield for identifying clinically relevant features of UTUC could prove to be of significant value. 3D visualizations of volumetric computed tomography (CT) data have previously been discussed as such, as those visualizations can improve imaging of UTUC including providing increased conspicuity of subtle lesions in the urinary upper tract [4].

Recently, a new method of generating 3D visualizations from volumetric imaging data has been described and is known as cinematic rendering (CR) [5–7]. Although much of the potential value of CR has yet to be quantitatively delineated through dedicated retrospective and prospective studies, the realistic shadowing effects and enhanced surface detail of the technique suggest possible roles in pre-operative planning, as well as an educational tool for residents and fellows, and a technology that may improve patient engagement and understanding. CR images demonstrate promise in cardiovascular imaging [8, 9], neuroradiology [10], bowel pathology [11], and renal conditions [12], among other potential applications. Expanding upon our prior experience with this technique for visualizing renal pathology [12], in this study we have provided a more-detailed overview of the possible utility of CR in UTUC.

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Technique

At our institution, CR images are created outside of the primary CT work-flow on a dedicated workstation (Siemens Syngo VB-30, Siemens Healthineers, Erlangen, Germany). The CR images are generated from standard CT acquisition parameters and can, in theory, be made from any CT data composed of isotropic voxels; no special hardware or acquisition protocol development is necessary. Just as with other 3D visualization methods, the images are created in an interactive way by the interpreting radiologist, a process that often takes under 5 min to complete. The time required to create the CR images is short enough that this methodology can be utilized for the vast majority of cases for which it may generate added value, even those of urgent/emergent nature.

The first step in creating CR images is the reconstruction of standard CT data into axial slices composed of isotropic voxels; these slices are then stacked to create a volume through which light will be passed [13]. Each voxel is assigned a color and transparency based on tissue composition as determined from attenuation [13]. These initial steps are shared in common with the methodology for traditional volume rendering (VR) [13]. However, it is at this point that the creation of CR or VR visualizations fundamentally diverges. For VR, light is passed through the volume using ray casting in which the pixel in the final 3D image is based on the additive contributions from each voxel through which the associated ray passed [13]. CR utilizes a much more complex process to pass light through the volume of isotropic voxels; intricate path tracing is used, in which numerous photons are propagated through the volume and the manner in which those photons interact with the component tissues within the volume (e.g., refraction and effects from component tissues in adjacent voxels) is realistically modeled [13]. The degree to which various tissues within the volume are displayed on the CR images is controlled by means of trapezoidal functions that assign attenuation values to percent transparency. Presets that are broadly useful for the display of different tissue types can be saved, and then manually adjusted by the interpreting radiologist at the time of CR image creation. The use of more than one trapezoid can allow for multiple tissue types with very different attenuations to be displayed on a single image.

The net result of CR visualization is photorealistic images with detailed shadowing, high levels of surface detail, and improved depth that can contribute to the more accurate display of the relative positions of objects within the imaged volume in comparison to 2D or traditional VR images.

Clinical examples

Four recent imaging examples of UTUC from three different patients imaged at our institution were retrospectively selected to demonstrate the principles of CR in this context. As these examples were selected to compose a case series for demonstration purposes, Institutional Review Board approval was not obtained.

Figure 1 includes images from a 66-year-old man with history of left nephroureterectomy for UTUC who has now presented with ureteroscopic findings of UTUC in the right renal pelvis and ureter, confirmed on biopsy. The CR visualizations can be appreciated on multiple contrast phases, similar to conventional images of urothelial carcinoma. Figure 1a (axial) is in the arterial phase and demonstrates abnormal thickening and enhancement of the right renal pelvis (red arrowheads). Figure 1b is a maximum intensity projection (MIP) image in the delayed/excretory phase that shows extensive irregularity of the contrast column within the renal pelvis corresponding to the foci of abnormal thickening and enhancement (red arrowhead). Figure 1c, and d is CR images from the same patient. Figure 1c (axial) is in the arterial phase, and the diffusely abnormal thickening and enhancement of the right renal pelvis is again appreciated (red arrowheads). Findings on the MIP in Fig. 1c are also recapitulated in Fig. 1d (red arrowhead), a CR visualization in the delayed/excretory phase. With the proper selection of window width and level, each contrast phase can provide CR visualizations, as is true with 2D and traditional 3D methods.

Figures 2 and 3 are derived from imaging studies on the same patient. In Fig. 2, the patient was 71 years old and underwent follow-up imaging for a known, biopsy-proven, non-invasive, low-grade papillary urothelial carcinoma of the right renal pelvis, which had originally been discovered three years earlier during an evaluation for microscopic hematuria. Figure 2a is a coronal 2D image in the delayed/excretory phase demonstrating a soft-tissue filling defect in the right renal pelvis (red arrowhead). The same finding (red arrowhead) is shown in the coronal VR image in Fig. 2b. Figure 2c and d is CR images, also in the delayed/excretory phase, in which the irregular filling defect in the contrast column is visualized with photorealistic detail and depth (red arrowheads). A narrower soft-tissue trapezoid was used for Fig. 2d relative to Fig. 2c, leading to absent visualization of some soft-tissue structures.

The patient in Fig. 2 was advised to have a nephroureterectomy; however, he declined and opted for observation. Figure 3 contains images from a follow-up study 2 years after the study depicted in Fig. 2. A new suspicious filling defect can be seen within the right ureter (red arrow) on the axial, 2D, delayed/excretory phase image in Fig. 3a. Figure 3b is a

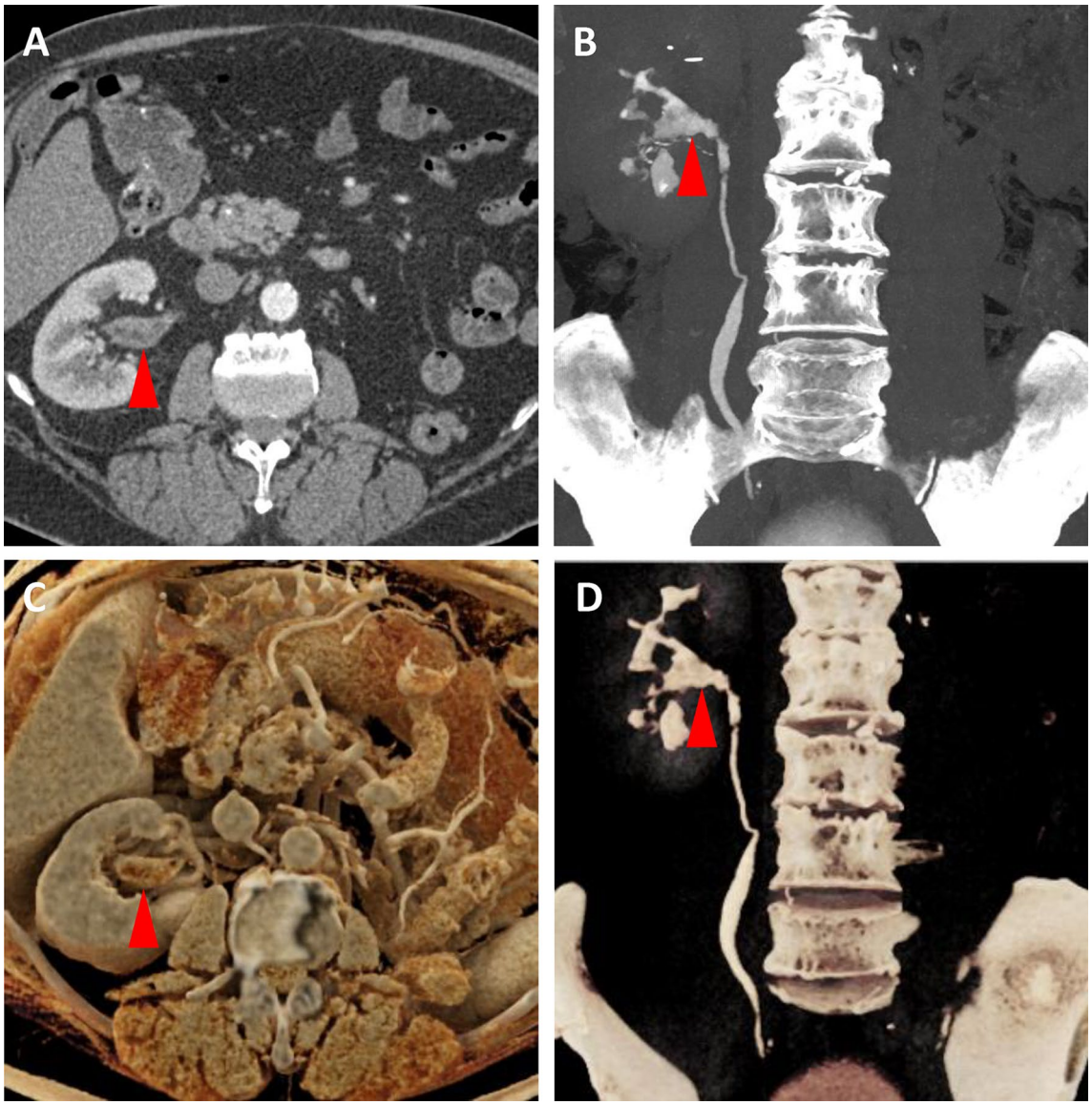

Fig. 1 A 66-year-old man with right UTUC. **a** Axial 2D CT image in the arterial/nephrographic phase shows diffuse thickening and enhancement of the right renal pelvis (red arrowheads), consistent with the diagnosis of UTUC. **b** Coronal MIP in the delayed/excretory phase shows corresponding extensive irregularity throughout the contrast-opacified right renal pelvis (red arrowhead). **c** Axial CR visualization in the arterial/nephrographic phase and **d** coronal CR visualization in the delayed/excretory phase demonstrate that these findings can also be shown to be advantageous to CR, so long as appropriate window width and level settings are utilized

coronal VR image that shows the original right renal pelvis filling defect (red arrowhead) as well as multiple new filling defects within the contrast column in the right ureter (red bracket), compatible with new multi-focal sites of urothelial carcinoma involvement. Figure 3c and d is CR images from the delayed/excretory phase; Fig. 3c shows the filling defect in the right renal pelvis (red arrowhead), although the ureteral findings are difficult to appreciate due to the similar display of excreted contrast and bone with this combination of window width and level. Utilizing an entirely different preset that was optimized for showing intraluminal findings within the contrast-opacified renal collecting systems and ureters, the CR image in Fig. 3d demonstrates both the right renal pelvis filling defect (red arrow) and the ureteral filling defects (red bracket). Of note, the apparent irregularity at the left ureteropelvic junction is actually just tortuosity of the ureter and not a new, contralateral site of disease; this emphasizes the need for the radiologist to review the 2D source images in addition to the CR images to provide the most accurate interpretation. Given the newly appearing sites of disease in the right ureter, the patient opted to pursue nephroureterectomy.

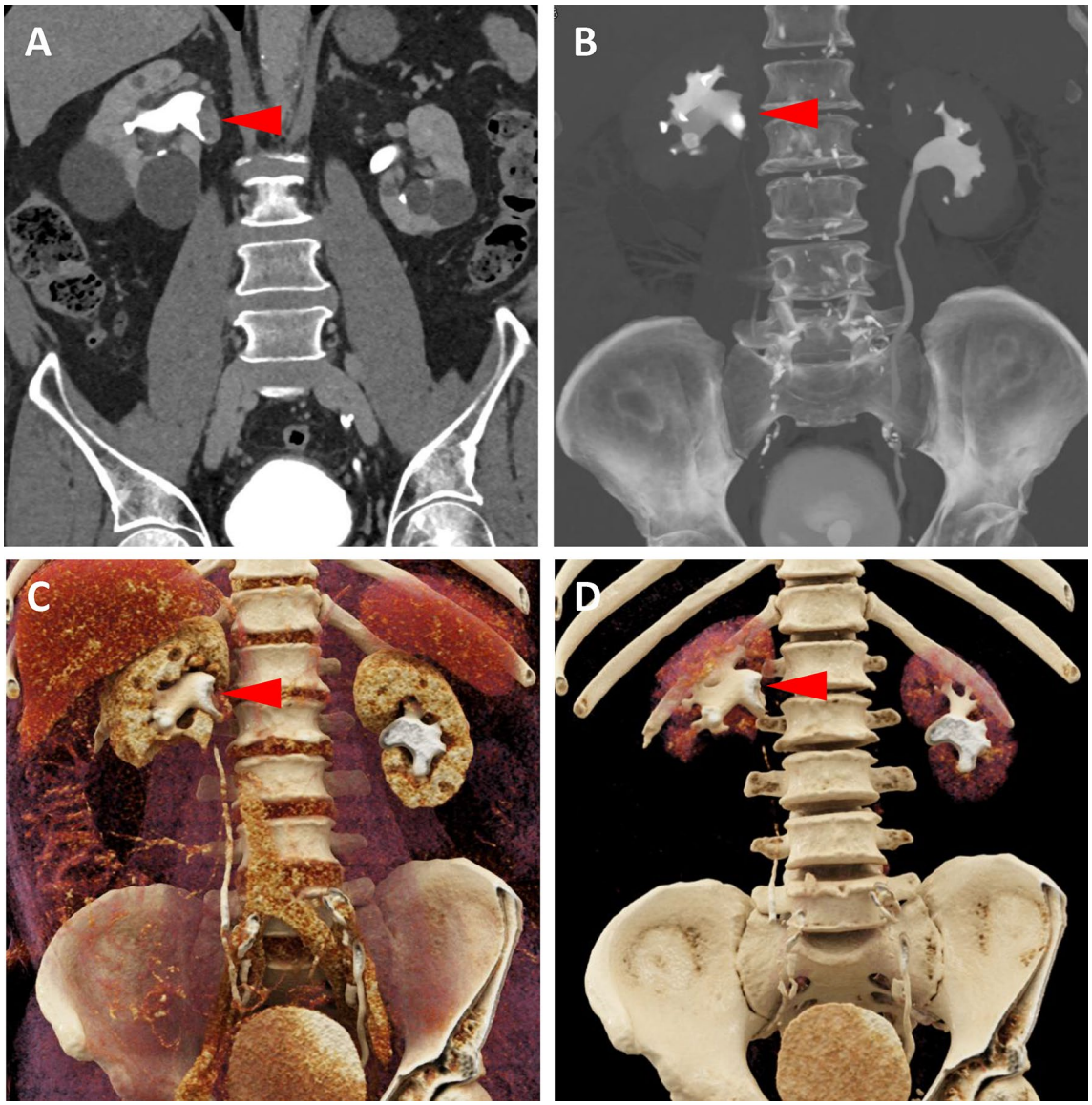

Fig. 2 A 70-year-old man with right renal pelvis UTUC. **a** Coronal 2D CT image in the delayed/excretory phase demonstrating a filling defect in the right renal pelvis (red arrowhead) which was subsequently diagnosed as a low-grade papillary UTUC. **b** Coronal VR image in the delayed/excretory phase also demonstrates the right renal pelvis UTUC (red arrowhead). **c**, **d** Coronal CR images, also in the delayed/excretory phase, provide photorealistic detail and added image depth while still displaying the right renal pelvis UTUC

Figure 4 is composed of images from a 73-year-old man with known low-grade UTUC of the left ureteropelvic junction being treated with intraluminal mitomycin C as part of a clinical trial. Figure 4a is an axial, 2D image in the delayed/excretory phase showing a papillary filling defect in the region of the left ureteropelvic junction (red arrowhead). This finding is shown with high conspicuity in the VR image in Fig. 4b. Figure 4c and d is CR visualizations of the left upper tract lesion. For both CR images, another preset that was optimized for intraluminal display was utilized, similar to Fig. 3d, although with overlying bone and highly enhancing soft tissue (such as the kidney parenchyma) also included. The papillary nature of the UTUC lesion is clearly seen due to the depth created by the shadowing effects intrinsic to CR images (red arrowheads).

The generation of Fig. 4c and d with detailed views of the urothelial surfaces along the upper tracks was accomplished with a preset that is shown as a voxel histogram in Fig. 5, and was applied to the delayed/excretory phase volumetric data. The dominant trapezoid in this preset is centered at a high attenuation and the plateau portion of the trapezoid is converged to a single point at the low end of the attenuation range.

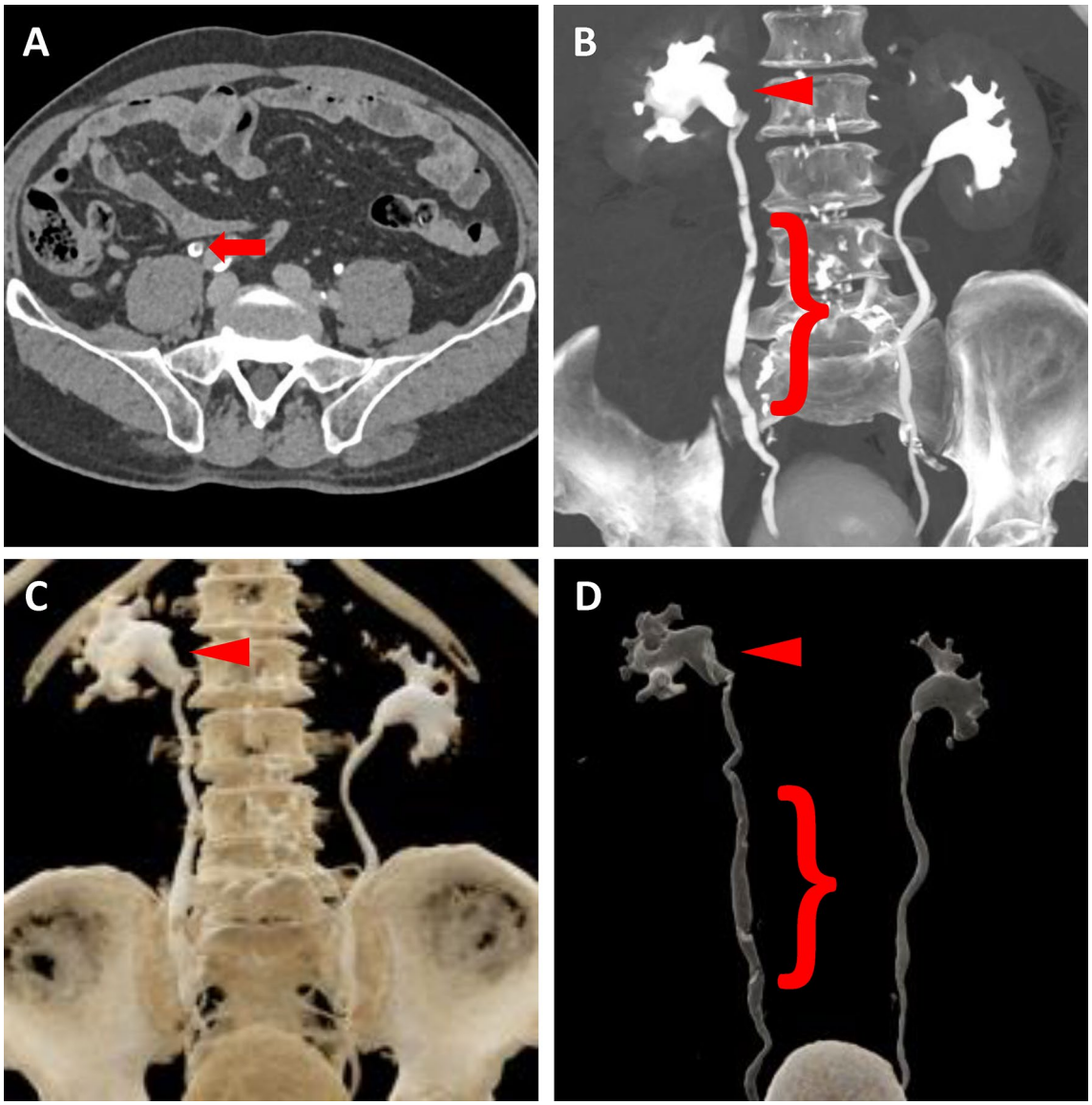

Fig. 3 A 72-year-old man (same patient as in Fig. 2) with right renal pelvis and right ureter multi-focal UTUC. **a** Axial 2D CT image in the delayed/excretory phase shows a new filling defect in the right ureter (red arrow). **b** Coronal VR image, also in the delayed/excretory phase, demonstrates both the dominant lesion in the right renal pelvis (red arrowhead) as well as multiple filling defects in the right ureter (red bracket), most compatible with multi-focal UTUC. **c**, **d** CR images both demonstrate the right renal pelvis UTUC (red arrowheads), although the ureteral lesions are best appreciated in (**d**), where the preset has been selected to exclude bone and has been optimized to display intraluminal findings within the collecting systems and ureters (red bracket). The visual irregularity at the left ureteropelvic junction in (**d**) is tortuosity of the ureter and not an additional site of disease, indicating the importance of reviewing 2D source images in conjunction with CR images

Discussion

Given the propensity of UTUC to behave aggressively, accurate diagnosis and staging information from imaging is of significant importance in guiding patient management. 2D CT findings, such as subjective tumor heterogeneity and irregular margins, as well as radiomic features such as entropy, can predict pathology features such as the depth of invasion [14]. Other features, such as tumor size, lack such predictive power [14]. Higher stage disease (i.e., invasion into the muscularis propria, or deeper) correlates directly with high-grade and fundamental biologic aggressiveness [15]. For all of these reasons, extracting the maximum possible information from imaging examinations of patients with UTUC is of pivotal importance. In the case series in this study, we demonstrate that CR visualizations can provide similar information to that obtained with standard 2D and 3D methods, although with improved surface detail and

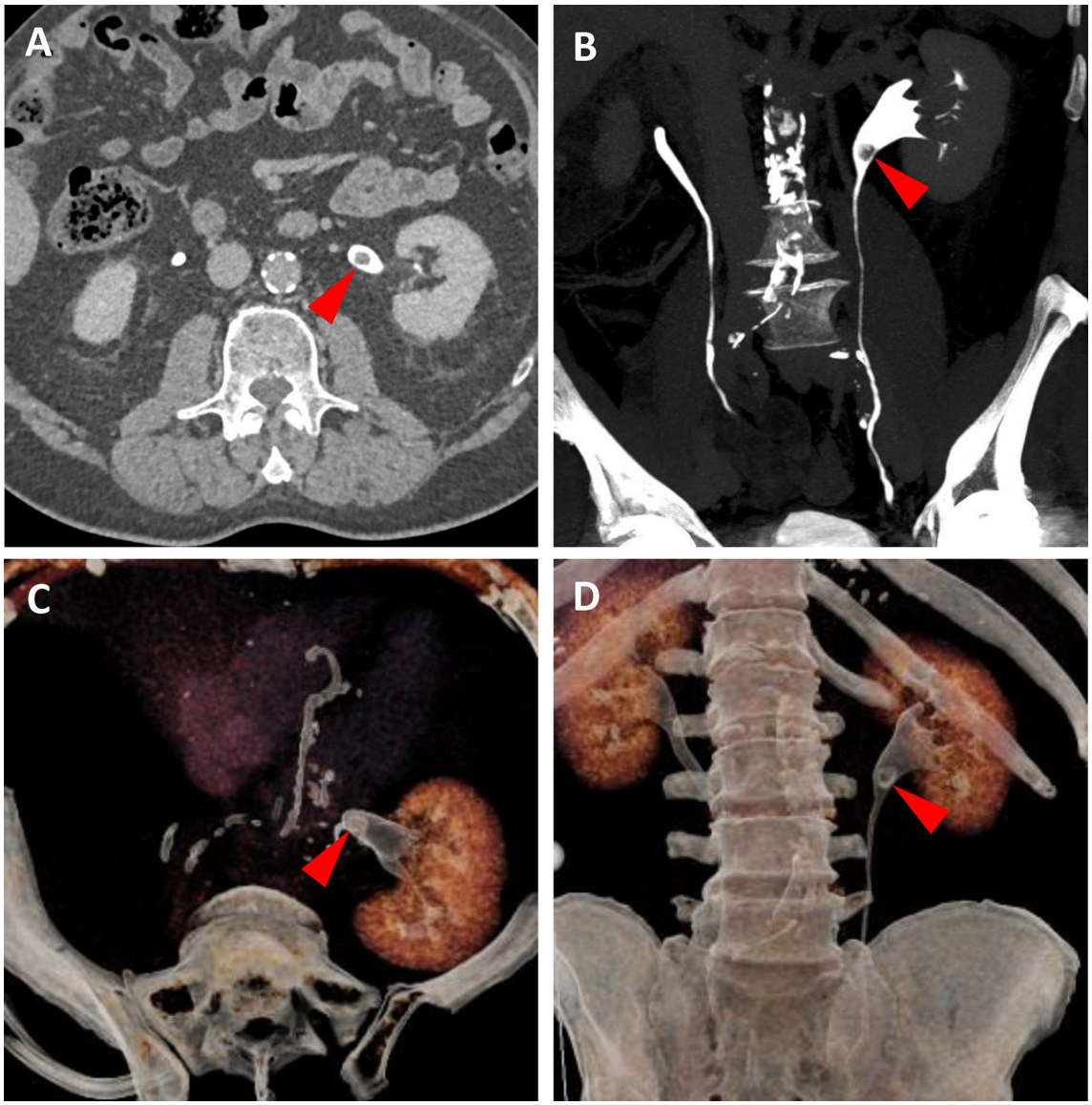

Fig. 4 A 73-year-old man with left ureteropelvic junction UTUC. **a** Axial 2D CT image in the delayed/excretory phase demonstrates excreted contrast surrounding a papillary filling defect consistent with the patient's known disease (red arrow). **b** Coronal VR image, also in the delayed/excretory phase, also demonstrates the filling defect (red arrowhead). **c** Axial and **d** coronal CR images utilizing a preset that allows for accentuation of the urothelial surfaces of the collecting systems and ureters. The patient's UTUC lesion is again demonstrated near the left ureteropelvic junction (red arrowheads)

greater image depth. Whether the features of CR add diagnostic value to the imaging of patients with UTUC should be investigated, particularly as this highly detailed visualization methodology may be able to elucidate subtle findings of muscle invasion or reveal textural changes within tumors that may have prognostic importance [16].

The ability to use multiple overlapping soft-tissue trapezoids to create complex variations in the visibility, translucency, and color of different structures within the imaged volume is another aspect of CR that requires further study. In the case series presented in this study, this principle of CR is perhaps best displayed in Figs. 3d and 4c, d, where the CR visualizations were manipulated to emphasize intraluminal details within the renal collecting systems and ureters. In a way, this could be thought of as similar to minimum intensity projection (MinIP) [17], although in our experience it has been possible to display intraluminal findings as well as preserve the display of other soft tissue types in a manner that is not typically performed with MinIP images. This type of visualization of the urothelial surface of the renal pelvis and ureters may aid in the detection of smaller tumors.

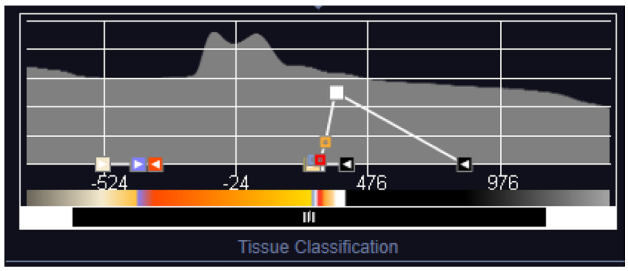

Fig. 5 Intraluminal preset voxel histogram. For the creation of CR images that demonstrate the intraluminal surfaces of the upper tracts (e.g., Fig. 4c, d), we utilize the preset shown on this voxel histogram

Much remains to be understood and explored in regard to utilizing CR in the evaluation of UTUC. However, regardless of the ultimate diagnostic utility, it is reasonable to expect that the intuitive nature of CR images and their accurate display of the relative positions of anatomic structures will facilitate the adoption of this visualization technique for trainee education and patient engagement.

Conclusion

As with other regions with complex anatomy for which 3D visualization is a helpful adjunct to standard axial and multiplanar reformatted images, the evaluation of UTUC with CR may ultimately be found to provide important information regarding lesion identification and characterization, as well as therapeutic planning. Further study of the role of CR in UTUC should be carried out to investigate the impact on lesion detection and classification as well as in patient triage and management.

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Compliance with ethical standards

Conflict of interest EKF receives research support from Siemens and GE Healthcare and is a co-founder and stockholder in HipGraphics, Inc. The other authors have no relevant conflicts of interest to report.

Ethical approval This manuscript does not detail a defined study and no ethical approval was necessary.

Informed consent No patient data is included in this manuscript and informed consent was not applicable.

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