

Applications and Prospects of Virtual Slice Technology in Nephrology Clinical Practice, Research, and Teaching: Postprint

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Abstract

Virtual slide, also known as digital pathology, employs linear scanning technology to perform comprehensive rapid scanning of entire glass slides, transforming traditional glass slides into whole slide images (WSI). The WSI scanning system comprises hardware devices including optical microscopes, slide scanners, and image acquisition equipment, together with image acquisition software. WSI is generated by acquiring high-resolution digital images through digital slide scanning devices, with software automatically performing seamless stitching processing. Through magnification operations, WSI can restore the original high-resolution images, which is fundamentally different from ordinary static images where zooming through viewing software only changes dimensions without improving resolution (Figure 1). WSI image software also enables users to rotate, edit, annotate, and conduct measurement analysis on images. In recent years, the application of interactive technologies has further enhanced the usability of virtual slides. Using “virtual slide,” “digital pathology,” and “whole slide image” as search terms in PubMed reveals that the number of related studies demonstrates a year-by-year increasing trend.

Full Text

Application Prospect of Virtual Slide Technology in Nephrology Clinical Practice, Research and Teaching

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Virtual slide technology, also known as digital pathology, employs linear scanning technology to rapidly capture entire glass slides in all dimensions, trans-

forming traditional specimens into whole slide images (WSI). A WSI scanning system comprises hardware components—including optical microscopes, slide scanning mechanisms, and image acquisition devices—along with specialized image acquisition software. The system captures high-resolution digital images through digital slide scanning equipment, which are then automatically stitched together seamlessly by software to create the final WSI. Unlike conventional static images that merely change size without improving resolution when zoomed through viewing software, WSI can restore the original high-resolution image through magnification operations, representing a fundamentally different capability (Figure 1 [Figure 1: see original paper]). WSI software also enables users to rotate, edit, annotate, and perform measurement analyses on images. In recent years, the application of interactive technologies has further enhanced the usability of virtual slides. A PubMed search using the terms “virtual slide,” “digital pathology,” and “whole slide image” reveals a year-over-year increasing trend in related research publications (Figure 2 [Figure 2: see original paper]).

While virtual slides have gradually begun to replace glass slides and traditional optical microscopes for pathology education and training, their adoption in nephrology teaching and training remains limited. Renal pathology represents both an important branch of pathology and an essential component of nephrology. Renal biopsy pathology plays a crucial role in diagnosing kidney diseases, formulating treatment plans, predicting prognosis, and investigating pathogenic mechanisms. This article elaborates on the applications and prospects of virtual slide technology in nephrology clinical practice, research, and education.

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Figure Captions

Figure 1. Comparison of viewing WSI using virtual slide browsing software (A and B) versus static images using conventional image viewing software (C). (A) Overview of renal tissue in virtual slide at lower magnification. (B) Local tissue observation after magnification, with no loss of resolution and ability to mark and annotate. (C) Magnified static image using conventional software showing decreased resolution.

Figure 2. Annual number of articles retrieved from PubMed using “virtual slide,” “digital pathology,” and “whole slide image” as search terms.

Clinical Teleconsultation

The feasibility of using virtual slides for clinical surgical pathology work, including primary diagnosis, has been validated by multiple studies, demonstrating

diagnostic concordance rates of 93%–97.7% with light microscopy. In 2017, the U.S. Food and Drug Administration (FDA) approved the first whole slide imaging system—Philips IntelliSite Pathology Solution (PIPS)—for clinical practice in digital pathology. Telepathology is not a new concept; it was first implemented at Massachusetts General Hospital in Boston in the 1960s [1], and its remote consultation systems have continuously evolved. Compared with traditional glass slides and static images, virtual slide technology offers numerous advantages in telepathology regarding image resolution, information integrity, and communication equipment requirements [2,3].

In the era of precision medicine, disease diagnosis has become increasingly complex and refined with the development of molecular pathology, making expert clinical opinions particularly critical for individualized treatment decisions. WSI technology enables more effective sharing of pathological information with clinical experts across vast distances, allowing multiple specialists from different countries and regions to simultaneously participate in consultations and discussions of difficult cases. Virtual slides enhance the efficiency of remote consultations, enabling more timely patient care, and patients thus become direct beneficiaries of this technology in clinical practice.

Research Applications

Early scientific research on virtual slide technology primarily focused on comparing its diagnostic concordance with traditional glass slides and assessing inter-pathologist reliability when using virtual slides for diagnosis. With the application of artificial intelligence in medicine, digital pathology research has advanced considerably. Through deep learning of image data from pathology databases, computers can analyze virtual slides, automatically detect lesion areas, and quantitatively evaluate various parameters to assist pathologists in achieving rapid, accurate, and highly reproducible diagnoses and pathological staging. Breast cancer research has seen relatively more progress in this area [4,5]. Multiple studies have demonstrated that Ki-67 index calculations by digital image analysis systems correlate well with pathologist-derived results and can predict recurrence-free survival [6,7]. Furthermore, since virtual slide scanning systems can capture images not only along the X and Y axes but also at different focal planes (Z-axis), latest technologies enable three-dimensional presentation of digital pathology sections, better demonstrating tumor growth patterns, though this remains in the exploratory stage [8].

Research on digital pathology in kidney disease lags behind, with only a few published studies in transplant pathology [9] and limited integration with emerging technologies like artificial intelligence and 3D imaging. This lag stems from several factors: the inherent complexity of renal pathology—characterized by intricate kidney structures, diverse cell types, numerous disease categories, and ongoing uncertainties or controversies in disease understanding—makes computer-based deep learning more challenging than in other histopathological fields. Additionally, many renal pathologists have yet to develop in-depth knowledge and

understanding of WSI. Consequently, virtual slide technology holds substantial untapped research potential in renal pathology.

Teaching Rounds and Clinical Pathology Discussions

Digital pathology plays an important role in undergraduate pathology education. By 2014, over 60% of medical schools in the United States had adopted digital pathology slides for teaching. WSI enhances learning outcomes in pathology; a randomized controlled study showed that learning groups using WSI images accompanying published online pathology articles scored 72% higher on assessments than control groups [10].

Nephrology teaching rounds predominantly involve clinical pathology discussions because they incorporate renal pathology findings. Complete renal pathology data must be presented during rounds to enable participants to obtain accurate pathological information and engage in focused, purposeful discussions. Digital images used for pathology teaching include static images, real-time dynamic images, and WSI. Currently, most nephrology teaching rounds in Chinese hospitals primarily use static images to display renal pathology. Despite capturing multiple images at different magnifications, static images cannot comprehensively demonstrate all pathological changes in renal biopsy specimens. Moreover, image quality is affected by numerous factors including slide preparation and staining, charge-coupled device (CCD) camera resolution, and image acquisition software parameters. Consequently, these limited static images may mislead participants and learners due to selection bias, potentially leading to erroneous conclusions.

Real-time dynamic images, though superior to static images, require optical microscopes and specialized CCD cameras, have specific space and lighting requirements that not all institutions can meet, and carry risks of loss or damage during glass slide transport. WSI can display the full spectrum of lesions in renal biopsy tissue without requiring specialized optical equipment at the teaching site, making it the optimal approach for nephrology teaching and clinical pathology discussions.

Furthermore, at national or regional nephrology conferences, clinical pathology discussion sessions often suffer from poor visibility due to large audiences, spatial limitations, and screen resolution issues, diminishing learning effectiveness for most attendees. WSI combined with wireless internet and mobile devices (smartphones, tablets) enables every participant to observe virtual slide information up close with self-controlled zoom capabilities. The Peking Union Medical College Hospital Pathology Department and Mayo Clinic have jointly hosted the Peking Union-Mayo Pathology Summit in recent years, applying virtual slide technology to pathology slide seminars with free online access to digitized pathological materials, receiving widespread acclaim from participants. Nephrology conferences at national and regional levels should similarly embrace this new technology for continuing education in renal pathology.

Specialist Training

Currently, no unified standards exist for renal pathology learning and assessment content in nephrology fellowship training programs domestically or internationally. Although most nephrologists lack formal pathology diagnostic credentials, systematic mastery of basic renal pathological lesions and common disease characteristics is essential for improving clinical practice. Nephrology fellowship training urgently needs to establish appropriate educational content for clinical physicians. Compared with traditional glass slides, digital slides are more easily shared anytime and anywhere. While glass slides from the same tissue block may show variations due to different sectioning planes, identical virtual slices provided online via local area networks standardize training content. Glass slide teaching requires expensive multi-headed microscopes, occupies considerable space, and slides fade over time, limiting learners' review opportunities. Many teaching cases involve rare diseases with limited paraffin tissue, making repeated sectioning and staining impossible. WSI overcomes these limitations of glass slides, offering portability, easy preservation, annotation capabilities, and convenient examination organization, making it particularly suitable for specialist training.

Multiple medical centers abroad have implemented virtual slide technology in fellowship training. Studies demonstrate that standardized online pathology training systems can stimulate learner interest and improve training outcomes [11,12]. Annotated digital pathology slides significantly improve resident test scores compared to unannotated slides (17% vs. 3%, $P=0.005$) [13]. The European Pathology Association has integrated WSI into the EUROpean Pathology Assessment & Learning System (EUROPALS) for periodic assessment of trainees' learning outcomes and competency evaluation [14]. Virtual slide technology not only standardizes training but also records learners' entire slide-reading processes [15], tracking which regions they examine, their navigation patterns (X and Y axes, zoom levels, and time spent), and annotations made. When combined with eye-tracking camera systems, even more information about medical decision-making processes can be captured [16]. These WSI tracking tools thus facilitate learner guidance and assessment while providing feedback to help improve diagnostic skills [15,17].

Several Chinese medical centers have piloted small-scale renal pathology courses for nephrologists using virtual slide technology. Learners examine virtual slides using software, describe pathological features based on brief clinical information, engage in group discussions, and reach final pathological diagnoses under instructor guidance and review. However, such in-person courses for nephrology specialists remain limited in participation and impact, requiring further systematization and online expansion. E-learning has become increasingly popular across medical fields due to its support for remote access, flexible scheduling, and cost savings. With gradual curriculum refinement, exemplary virtual slides of teaching value could be shared online with nephrologists at primary-level hospitals, demonstrating exemplary practices and exerting broader influence.

Virtual slide technology serves as a common tool in pathology e-learning, and interactive WSI can also facilitate problem-based learning (PBL) [18].

Issues Requiring Attention

Despite these advantages, several potential concerns warrant careful consideration. First, implementation costs: virtual slide technology requires high-resolution WSI scanning systems and optimized algorithm software, necessitating substantial upfront investment (often exceeding several million yuan). Additional expenses include storage space, scanning personnel, and equipment network maintenance and upgrades. Second, storage requirements: a single WSI of a renal tissue specimen at 40× magnification typically requires hundreds of megabytes of storage space, necessitating massive storage systems and backup solutions for large virtual slide databases to prevent data loss. Third, data transmission speed: the large file sizes of virtual slices require sufficient bandwidth for online sharing and interaction; otherwise, slow transmission speeds become unacceptable. This requires coordination with hospital information technology departments to ensure efficient data transfer. Fourth, data security and patient privacy protection: data used for online teaching and training should obtain appropriate ethical approval, with all patient-identifying information removed before use, while strengthening oversight to prevent unauthorized appropriation of pathology resources.

Conclusion

Virtual slide technology has begun to replace traditional glass slides and microscopes for pathology teleconsultation, research, and teaching, yet its adoption in nephrology remains limited. Given its clear advantages and broad development prospects over conventional glass slides, nephrologists should draw upon pathology department experiences, integrate discipline-specific characteristics, and fully leverage this new technology to better serve nephrology clinical practice, research, education, and training.

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