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The current state of digital cytology and artificial intelligence (AI): global survey results from the American Society of Cytopathology Digital Cytology Task Force

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Introduction The integration of whole slide imaging (WSI) and artificial intelligence (AI) with digital cytology has been growing gradually. Therefore, there is a need to evaluate the current state of digital cytology. This study aimed to determine the current landscape of digital cytology via a survey conducted as part of the American Society of Cytopathology (ASC) Digital Cytology White Paper Task Force.
Materials and methods A survey with 43 questions pertaining to the current practices and experiences of WSI and AI in both surgical pathology and cytology was created. The survey was sent to members of the ASC, the International Academy of Cytology (IAC), and the Papanicolaou Society of Cytopathology (PSC). Responses were recorded and analyzed.
Results In total, 327 individuals participated in the survey, spanning a diverse array of practice settings, roles, and experiences around the globe. The majority of responses indicated there was routine scanning of surgical pathology slides (n = 134; 61%) with fewer respondents scanning cytology slides (n = 150; 46%). The primary challenge for surgical WSI is the need for faster scanning and cost minimization, whereas image quality is the top issue for cytology WSI. AI tools are not widely utilized, with only 16% of participants using AI for surgical pathology samples and 13% for cytology practice.
Conclusions Utilization of digital pathology is limited in cytology laboratories as compared to surgical pathology. However, as more laboratories are willing to implement digital cytology in the near future, the establishment of practical clinical guidelines is needed.

Introduction

Medicine has been transformed in recent years with the large-scale integration of computer technology and artificial intelligence (AI). Medical specialties such as radiology have undergone major advances with transformation from analog to digital methods.[1] Additionally, there have been a growing number of health care AI applications for clinical purposes ranging from billing, to diagnostic evaluation and workflow optimization.[2-5] Anatomic pathology has also begun this transition with the advent of large-scale whole slide imaging (WSI) for clinical purposes. A growing number of pathology laboratories have now begun utilizing digital WSI for tissue evaluation and diagnosis, with some replacing the light microscope in daily practice.[6-9] This adoption has been slower in cytopathology mainly due to differences in sample preparation and the associated technical difficulties (e.g., focus) in WSI.[10,11] However, through recently improved scanners, infrastructure, and increasing experience with adoption in surgical pathology, many cytopathology laboratories have also begun WSI adoption.[12-14] At the same time, AI applications have emerged for clinical implementation in cytopathology practice.

To address the expanding presence of WSI and AI applications in cytopathology, the American Society of Cytopathology (ASC) created a Digital Cytology Task Force. The task force findings culminated in 2 white papers that were recently published to fill knowledge gaps and provide recommendations for both digital cytopathology and AI.[15,16] As a part of the task force objectives, a global survey was distributed to better understand the current state of digital cytopathology and AI in the global cytopathology community, along with current perceptions and needs. Prior surveys regarding digital pathology have been published, however none specifically addressed WSI and AI trends in cytopathology.[9,17,18] A few digital cytology−specific survey studies also have touched upon digital cytology, but mainly in the form of telecytology/rapid onsite evaluation and not WSI.[19,20] Understanding the current state and opinions in this digital era is a critical aspect to help address the specific needs of the cytopathology community to provide future resources and guidelines. This paper presents the findings of the Global Digital Cytology Task Force survey to enhance the understanding of current trends and opinions in digital cytopathology and AI. A select portion of the survey was previously published along with parts 1 and 2 of the Digital Pathology White Paper Task Force in the *Journal of the American Society of Cytopathology*.[15,16]

Material and methods

Utilizing virtual meetings and e-mail correspondence, the ASC Digital Cytopathology White Paper Task Force curated a series of survey questions based on current peer-reviewed literature and expert experience. The questions were developed to assess the following objectives:

1. The current state of cytopathology WSI utilization across different geographic regions and practices.
2. Workflow trends and specifications for cytopathology WSI.
3. The perceived benefits, challenges, and needs of cytopathology WSI adoption.
4. The current state of cytopathology AI.
5. Perceptions towards AI in cytopathology practice including concerns and needs to encourage adoption.

The final survey comprised 43 questions encompassing multiple choice and free text questions (Supplemental Document 1). General information regarding the participants' practice location, experience, and roles were also included. The questions presented to participants varied based on their answers. If the participant answered "no" to the question "do you scan cytopathology slides?", then subsequent questions asking further details regarding their cytopathology WSI workflow were skipped. If the participant answered "yes", they were then further directed to questions regarding details of their WSI workflow. The same series of questions applied to the question of "do you scan surgical pathology slides".

The final survey was distributed by e-mail to the listservs of the ASC, Papanicolaou Society of Cytopathology (PSC), and the International Academy of Cytopathology (IAC) via the platform SurveyMonkey on behalf of the Digital Cytology White Paper Task Force. Once distributed the survey response period lasted from March 9, 2023, to April 1, 2023, and concluded approximately after a 1-month period.

Statistics

The survey responses were recorded by Excel (Microsoft, Redmond, WA) and then analyzed using Microsoft Excel and R (The R Project for Statistical Computing, Vienna, Austria). Percentages were calculated for categorical variables and select variables were displayed as stacked bar charts made by Microsoft PowerPoint (version 2023). Significance was evaluated using a 2-sided Fisher's Exact test for survey results regarding slide scanning by practice setting and geographic region. A P-value of <0.05 was considered statistically significant.

Results

In total, voluntary responses from 327 participants were collected. Responses came from various regions of the globe as well as different practice settings and from individuals with varying professional roles. Responses came from North America (n = 194; 59%), Asia (n = 96; 29%), Europe (n = 22; 7%), Africa (n = 5; 2%), Oceana (n = 4; 1%), and South America (n = 3; 1%), in decreasing order of frequency. Pathology practice settings included academic (n = 149; 71%), non-academic/community (n = 38; 18%), commercial/industry (n = 19; 9%), and government (n = 4; 2%). Of the responses, 129 were from staff pathologists (60%) of which 29 were laboratory directors, 42 cytologists (22%), 22 lab supervisors (12%), 8 trainees including medical students/residents/fellows (3%), and 5 research scientists (3%). Experience with cytopathology and digital pathology also varied, with many reporting >10 years of cytopathology experience (n = 132; 70%), 15% (n = 29) with 5-10 years, 12% (n = 22) with 2-4 years, and 3% (n = 6) with <1 year of experience. Participants had fewer years of experience with digital pathology compared with overall pathology practice, with 42% (n = 76) indicating 2-4 years of experience with digital pathology, 33% (n = 60) with <1 year, 19% (n = 34) with 5-10 years, and 7% (n = 12) with >10 years of experience.

Current cytopathology WSI workflow practices

Most respondents (n = 176; 54%) indicated that in their practice they do not scan cytopathology slides; 46% (n = 150) reported that they do scan cytology slides. In comparison, 61% (n = 134) responded that they do scan routine surgical pathology slides, with 39% (n = 85) reporting that they do not scan surgical pathology slides. However, this difference in scanning of cytology and surgical pathology slides did not meet statistical significance ($P = 0.09$). When asked about any future plans at their laboratory to scan either cytopathology slides or surgical pathology slides if not already, 36% (cytology: n = 78, surgical pathology: n = 66) planned to scan cytopathology and surgical pathology slides in the near future. However, more individuals indicated that they are not planning on (n = 31; 14%) or are unsure (n = 69; 32%) for cytopathology WSI compared with surgical pathology WSI, as 7% (n = 13) did not have plans and 29% (n = 53) were unsure.

Digital scanning trends were similar for cytopathology and surgical pathology WSI by geographic region and practice settings (Fig. 1). By region, North America (cytology: n = 82; 42%, surgical pathology: n = 95; 69%) and Asia (cytology: n = 57 [59%], surgical pathology: n = 32 [56%]) had the greatest number of participants that scan cytopathology as well as surgical pathology samples ($P = 0.01$). By percentage, Oceana (cytology: n = 2 [50%], surgical pathology: n = 0 [0%]) responses demonstrated a high percentage scanning cytopathology samples, although survey responses were low in this region. By practice setting, most participants who scan cytopathology and surgical pathology slides were from academic centers (cytology: n = 69 [46%], surgical pathology: n = 95 [73%]) compared with non-academic/community practice (cytology: n = 10 [26%], surgical pathology: n = 9 [26%]). Government laboratories (cytology: n = 2 [60%], surgical pathology: n = 3 [60%]) reported a higher percentage for scanning WSI, but overall response rates were low. A high percentage of participants at commercial laboratories/industry labs scan surgical pathology slides (n = 12; 60%) but less so for cytology slides (n = 6; 16%). Geographic and practice differences in slide scanning was shown to be significant for surgical pathology samples ($P < 0.01$) but not cytology samples ($P = 0.1$).

Of the participants that do scan cytology slides (n = 150), 17% (n = 25), they reported utilizing multiple scanners for cytology WSI with the most common scanners being Leica (n = 32; 29%), Hologic (n = 26; 24%), Philips (n = 24; 22%), Hamamatsu (n = 14; 13%), 3DHistech (n = 10; 9%), and Grundium (n = 5; 5%). Due to different slide preparations used in cytology and workflow considerations, it is possible that different scanners are optimal for specific preparations. Scanners utilized for surgical pathology slides were less varied, with the most common scanners used by participants including Philips (n = 48; 39%), Leica (n = 46; 37%), Hamamatsu (n = 16; 13%), Roche Ventana (n = 11; 9%), and 3DHistech (n = 8; 7%). For cytology preparation types that are scanned, cell blocks (n = 66; 63%), immunohistochemistry stains (n = 61; 58%), smears (n = 60; 57%), and liquid preparations (n = 84; 80%) were scanned at similar percentages with a lower percentage of scanning slides from Cytospin preparations (n = 28; 27%). However, 30% (n = 45) of respondents did not know which exact preparations were scanned.

Technical workflow details for WSI were also important to gauge. Most cytology slides were scanned

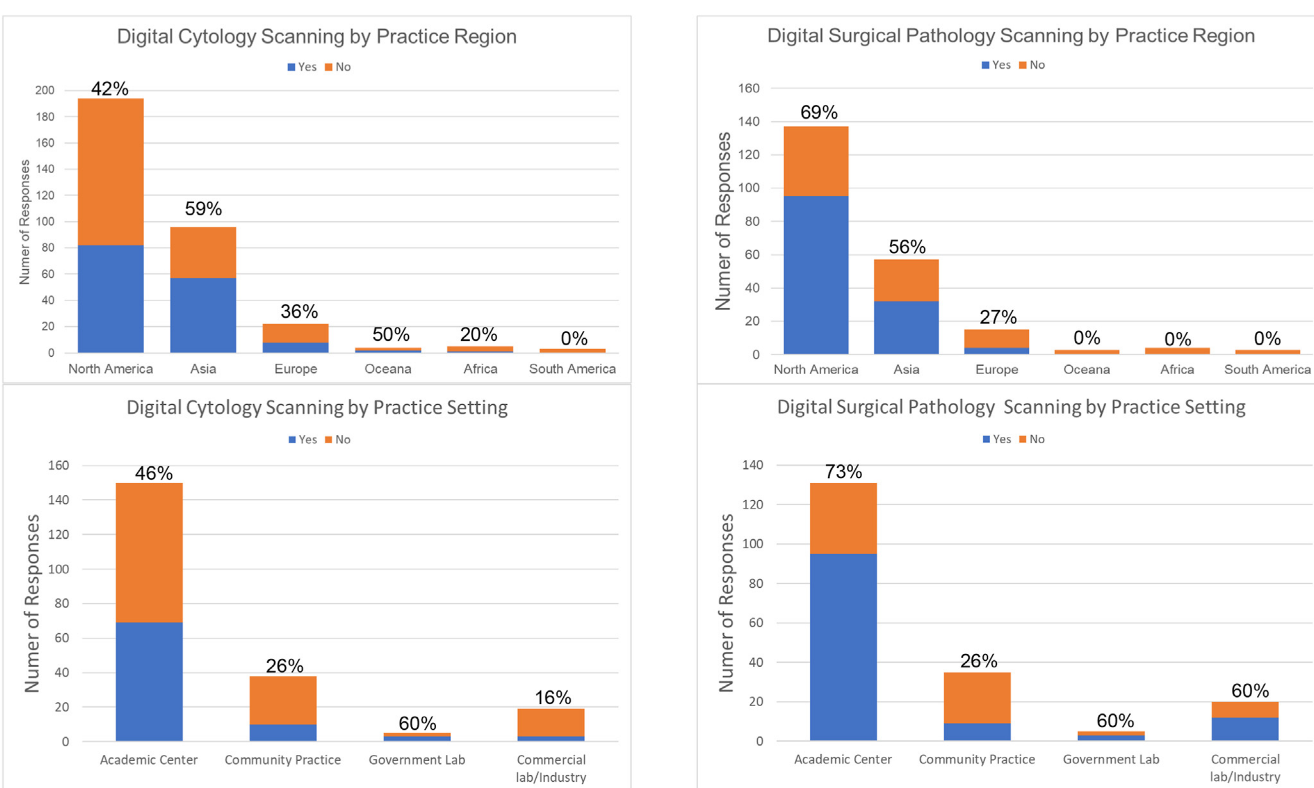

Figure 1 Digital slide scanning by practice region and setting.

at 40× magnification (n = 51; 48%), although many respondents also indicated that they scan at 20× (n = 44; 42%) as the highest magnification. As cytology samples pose the unique challenge of focusing on 3-dimensional cellular material for WSI, the use of Z-stacking was asked. Most individuals reported scanning cytology slides without Z-stacking (n = 70; 67%). In comparison, most individuals who scan surgical pathology slides scan at 20× magnification (n = 70; 48%) compared with 40× (n = 40; 34%).

How WSIs were utilized in practice showed a greater use of cytology slides for ancillary purposes such as trainee education (n = 52; 49%), case archiving (n = 46; 43%), and research (n = 39; 36%) compared with primary clinical uses such as for diagnostic review (n = 16; 15%) and in-house consultations (n = 17; 16%). Regarding uses specific to cytopathology, 11% (n = 12) utilized cytology WSI for rapid onsite evaluation (ROSE) and 28% (n = 30) for primary screening. Other areas where cytology WSI was used included QA/QC (n = 20; 19%) and consults from external institutions (n = 18; 17%). By comparison, the reported usage of surgical WSI demonstrated greater use of surgical WSI for primary diagnosis/evaluation (n = 55; 45%) and in-house consultations (n = 49; 40%). Ancillary uses were also higher with 51% (n = 63) of participants using surgical WSI for archiving, 64% (n = 79) for education, and 46% (n = 9) for research (Fig. 2). Overall, more responses were collected for the utilization of surgical WSI in daily practice (n = 123) compared to cytology WSI (n = 106) across the various tasks.

Responses regarding the major benefits of WSI were similar between surgical and cytology samples. Some of the choices with the highest responses included the ability to apply AI algorithms (cytology: n = 125; 57%, surgical pathology: n = 101; 54%), the ability to remotely sign-out (cytology: n = 113; 51%, surgical pathology: n = 108; 57%), digital consultation (cytology: n = 105; 48%, surgical pathology: n = 92; 49%), and the ability to use digital tools such as digital rulers and annotations (cytology: n = 92; 42%, surgical pathology: n = 88; 47%). Regarding ROSE, 44% (n = 96) indicated cytology WSI as a major benefit.

The major challenges in using WSI differed slightly between cytology and surgical WSI. The most reported major challenge for cytology WSI was poor image quality (n = 153; 70%) and difficulty interpreting morphologic features (n = 138; 63%), whereas for surgical WSI cost was the most reported challenge (n = 113; 62%) followed by difficulty in viewing/interacting with digital slides (n = 95; 52%). For surgical WSI, 50% (n = 91) indicated poor image quality as a challenge with 48% (n = 89) indicating difficulty with morphologic features. Questions regarding areas of improvement were consistent with the responses to challenges encountered for surgical and cytology WSI (Fig. 3). For cytology WSI, most responses for areas of improvement included better scanning technology (n = 158; 72%), better image quality (n = 138; 63%), cost (n = 119; 55%), faster image loading (n = 100; 46%), better software integration (n = 92; 42%), and the need for regulations/guidance (n = 92; 42%), amongst others. In comparison, for surgical WSI the highest responses included cost (n = 94; 51%), faster image loading (n = 84; 45%), scanning technology (n = 74; 40%), better image quality (n = 71; 38%), better software integration (n = 71; 38%), and lack of regulations (n = 55; 30%). When asked how useful practice recommendations would be for digital cytology most either responded very useful (n = 84; 38%) and useful (n = 79; 36%) compared to neutral

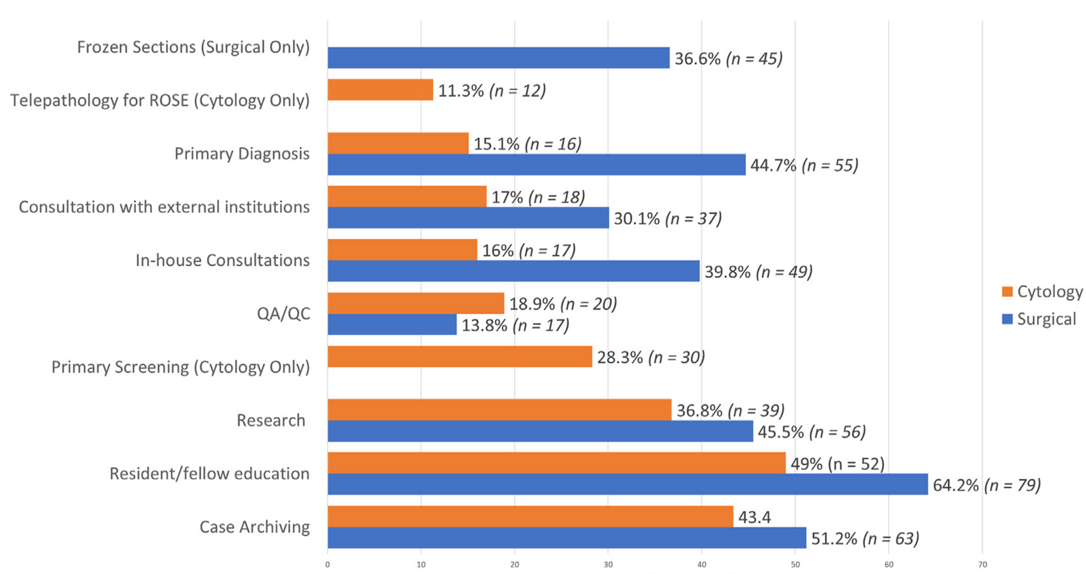

Figure 2 Areas of digital pathology utilization for cytology and surgical WSI.

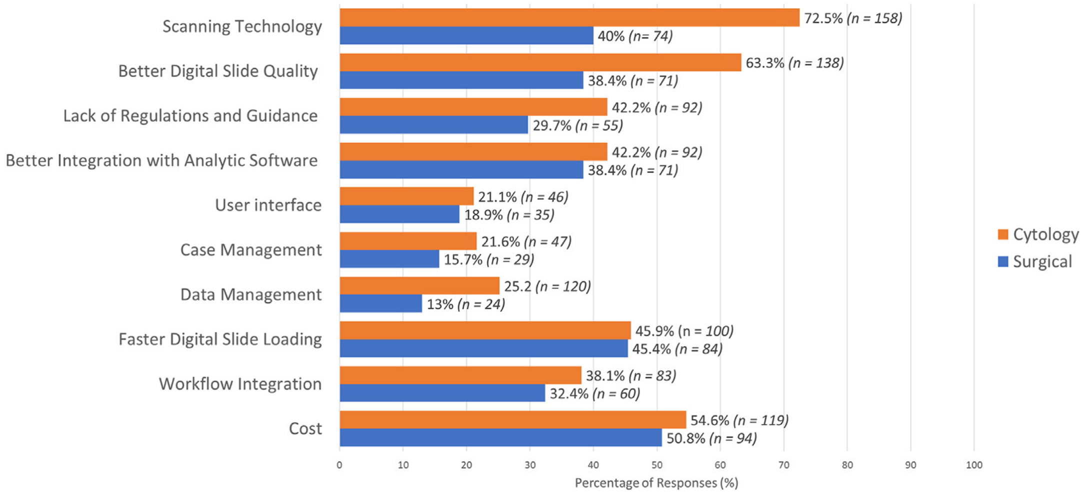

Figure 3 Areas that warrant improvement in cytology and surgical WSI.

(n = 43; 20%), minimally useful (n = 9; 4%), and not useful (n = 4; 2%).

The current state and trends of AI in cytology

AI utilization in surgical vs cytology practice

Participants reported similar rates of using AI in their clinical practice with 84% (n = 230) not using AI for cytology and 77% (n = 158) not using AI for surgical pathology. Amongst those that use AI in cytology practice the most common use was screening cytology samples (n = 180; 81%) followed by tumor classification (n = 9; 20%), biomarker quantification (n = 7; 15%), and quality assurance/quality control (QA/QC) (n = 3; 7%). For AI in surgical pathology practice, more individuals reported using AI for biomarker quantification (n = 22; 65%), tumor classification (n = 14; 41%), QA/QC (n = 10; 29%), metastasis detection (n = 10; 29%), tumor grading (n = 8; 23%), and billing (n = 3; 9%).

Opinions as to which areas AI could improve clinical practice were also surveyed to guide any future AI development (Fig. 4). For cytology AI, responses indicated a need for assistance with screening samples with 73% (n = 162) of responses for gynecology cytology, 46% (n = 102) for urine cytology, 32% (n = 71) for fluid (effusion) cytology, and 22% (n = 49) for fine-needle aspirations. Other areas where AI would be useful in cytology practice included biomarker quantification (n = 138; 62%), QA/QC (n = 83; 38%), and billing (n = 32; 14%). For surgical pathology AI, perceived need was seen in biomarker quantification (n = 156; 85%), metastasis detection (n = 78; 42%), tumor grading (n = 56; 30%),

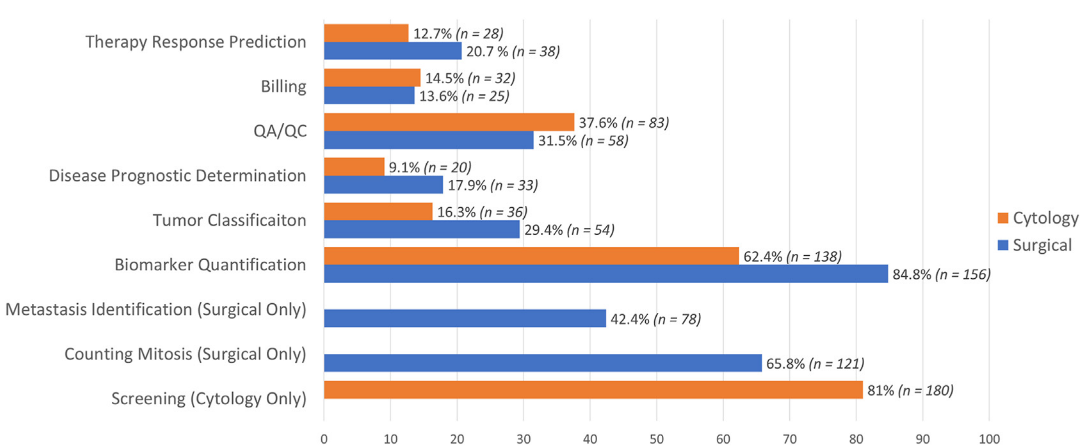

Figure 4 Areas of cytology and surgical pathology practice where AI implementation could be most useful.

QA/QC (n = 58; 31%), prediction of molecular alterations from hematoxylin and eosin images (n = 42; 23%), tumor classification (n = 54; 29%), and billing (n = 25; 14%).

Comfort level in using AI for cytology practice

Comfort level in adopting AI for clinical practice based upon its approval status by a regulatory body such as the U.S. Food and Drug Administration (FDA) were also assessed. Most participants indicated that they would be more comfortable with using an AI algorithm approved by a regulatory body, with 36% (n = 81) indicating they would be comfortable, 12% (n = 27) being very comfortable, 29% (n = 66) being neutral, and 8% (n = 17) not being comfortable using such an algorithm. For potential AI algorithms that have not been approved by a regulatory body, 45% (n = 101) indicated they would not be comfortable with using such a tool, 6% (n = 13) saying they would be comfortable, and 1% (n = 3) being very comfortable with such algorithms.

Assessing AI algorithms

For assessing (ie, validating performance for intended use) AI algorithms, participants would find it most helpful to evaluate either a series of representative images that were classified by the AI algorithm, selected regions of interest over the digital slide such as heatmaps, as well as numerical values such as sensitivity and specificity. Other metrics that participants mentioned would be useful are area under the receiver operator curve (n = 82; 37%) and prediction annotations on the digital slides (n = 107; 48%). As to how many cases would be appropriate for validation of an AI algorithm, many responded with 100 (n = 67; 31%) or 200 (n = 66; 30%) cases. However, additional answers ranged from needing 500-1000 cases for AI validation.

Discussion

Digital pathology in the form of WSI and AI has shown many benefits across various aspects of pathology practice.[4,21,22] Over the past decade increasingly more pathology departments have begun scanning pathology slides as WSI for clinical practice. More recently, AI algorithms geared specifically towards pathology have also grown.[23-27] However, digital integration and the implementation of new technology, although beneficial, requires a large effort and change to daily workflow. Additionally, a major challenge in the adoption of new technology is the novelty of the technology and lack of clinical experience in the field. As digital pathology and AI become more prevalent, it is important to gauge the current trends within the cytology community as well as the needs, concerns, and perceptions.

Responses to the ASC Digital White Paper Task Force survey were collected across various practice settings, end-user roles, and geographic locations. Initial general results were published in the respective digital cytology whitepaper task force papers to support the recommendations/guidelines.[15,16] This report delves further by expanding in detail the development of the survey and its complete results. Analysis in the differences of digital cytology/surgical pathology practice by setting and region as well as additional unpublished data such as the types of scanners utilized by users, responses pertaining to surgical pathology samples, and preference for AI assessment amongst others are included.

Survey data revealed that many individuals report scanning cytology slides at their laboratories, particularly among academic centers. This trend is similar to that reported for digital pathology overall and telecytology, with more academic centers scanning slides.[28] Survey results from Chen-Yost et al. regarding digital cytology trends showed that 56% of individuals use digital cytology similar to our results of 46%.[20] However, more respondents to our survey indicated that they scan surgical pathology slides more frequently compared with cytology slides. Many of the participants who did not scan either cytology or surgical pathology slides did indicate plans to scan slides in the near future. This suggests that more cytology laboratories will be integrating WSI into their practice in the next few years.

For those who did engage with WSI, it was important to assess the technical details of their digital workflow to better understand how cytology slides were being scanned in practice. Scanning of slides was performed using a variety of WSI scanners/platforms, the majority of whom reported using Philips or Leica devices. Scanners from Hologic, Hamamatsu, and 3DHistech also were reported by a high number of participants. No single dominant WSI scanner/platform was seen from the survey data, indicating that a diverse array of choices are available on the market when it comes to buying WSI scanners. As to scanning specifications, cytology samples were scanned mostly at the higher magnification of 40×, compared with 20× for most surgical pathology slides. The higher scanning objective for cytology samples is consistent with the nature of cytologic evaluation, as closer cytomorphologic evaluation is often needed. Most individuals reported not scanning with multiple layers such as Z-stacks. However, this may be due to technologic limitation as not all slide scanners have Z-stacking capabilities.

How cytology and surgical pathology WSI were utilized in daily practice also differed. For those who utilized cytology WSI, much of their use was directed towards archival purposes, education, and research rather than for diagnostic review. However, some participants did note using cytology WSI for diagnostic review as well as for teleconsultation and screening. This trend may change, especially in the post-COVID-19 era, as a recent study has shown an increase in digital adoption for cytology practice. Particularly for telecytology/ROSE, there was an increase in usage post-COVID. While our survey results indicated that 11% of participants use digital cytology WSI for ROSE, these responses are regarding WSI specifically and does not include other modalities for ROSE such as live streaming. More importantly, perception towards the usefulness of cytology WSI in practice increased from 29% to 43%, in line with the cytology WSI interest seen in this survey and its importance.[20] This is in comparison to surgical pathology WSI for this survey where a greater number of individuals utilized digital slides for teleconsultation purposes, as well as primary diagnosis, archiving, research, and education. A prior survey noted that 60% of centers in the United Kingdom utilized surgical WSI similar to the 61% of participants that do scan surgical WSI in this survey.[17] This difference may be attributed to technology impact on image quality due to the nature of cytology samples leading users to be less comfortable using cytology WSI for diagnostic purposes than surgical pathology WSI. Additionally, adoption of surgical pathology WSI into clinical practice is further along in terms of experience, regulatory approval and guidance compared to cytology WSI.

The issues and challenges facing cytology WSI stem from the difference in slide preparation. It is well known that due to the 3-dimensional nature of the cytology samples as well as the disbursement of cells and the greater need to evaluate cellular details leads to difficulty in quality WSI acquisition.[10,11] This difficulty is mirrored in the survey responses as the largest challenges with cytology WSI were poor image quality and morphologic features. This is again in line with prior digital cytology survey findings where the inability to focus and image quality issues were the major barrier to using digital cytology clinically.[20] Conversely, cost and interface difficulties were the highest challenge for surgical WSI in addition to image quality issues. Interestingly the perceived major benefits of WSI were similar between cytology and surgical WSI with the prospect of AI development, remote sign-out/telecytology, and digital consultation amongst the highest cited for both WSIs.

Based on the survey response, AI algorithms are currently not widely used for either cytology or surgical pathology practice. Only a minor group of responses indicated using AI algorithms. For those who did use AI algorithms, most were for biomarker quantification such as Ki67 quantification for both surgical and cytology samples and tumor classification. Currently, not many AI algorithms are widely adopted for clinical use. Only recently have commercial AI algorithms specifically geared toward pathology including cytology have emerged. As to where AI algorithms may have the greatest benefit, biomarker quantification, tumor classification, and QA/QC ranked among the highest for both cytology and surgical samples. Similar responses were seen in prior AI survey studies primarily for surgical pathology samples, reinforcing the need for AI in areas such as biomarker quantification and treatment response.[18] For cytology specifically, AI for screening samples was also strongly suggested. Such responses may help guide AI companies or research in development towards these areas of perceived need. Additionally, participants would be more comfortable and willing to adopt AI algorithms that have been approved/cleared by a regulatory body such as the FDA. Many stated that guidelines and clearer regulations around AI for pathology is needed.

A few limitations should be noted, stemming from an uneven distribution of responses from certain practice settings as well as geographic region. Most of the responses came from academic centers compared with other practice settings. This may be due to more interest and engagement among individuals at academic practices. Another bias was that more responses were received from North America and Asia compared with other regions of the globe. While possible that there are fewer members of the cytology community in some regions, low numbers were also seen in regions such as Europe and South America, which are known to have many cytopathology labs. More targeted surveys, particularly those with low responses, related to digital cytology and AI in the future would help better assess trends in specific geographic regions and practice settings. Finally, although the survey questions tried to address trends comprehensively, more detailed data regarding workflow specifics and AI were not included to decrease the burden of completing the survey to encourage participation. Future surveys that include more in-depth questions related to digital infrastructure, turnaround time, and funding, among a few, should be considered.

Conclusions

This paper summarizes the results of the ASC Digital Cytology White Paper Task Force survey conducted in 2023. The results show that the integration of WSI and AI into cytology practice is still new, with only a few practices utilizing them presently. Compared with surgical pathology WSI, adoption of cytology WSI lags and is currently being utilized mainly as an ancillary tool for daily practice rather than primary diagnostic evaluation. Nevertheless, there is growing interest in the use of cytology WSI coupled with AI, especially for screening liquid-based Papanicolaou tests. In order to help drive digital cytology forward, guidelines and recommendations of how to incorporate and evaluate cytology WSI and AI into practice are needed.

Conflict of interest disclosures

The authors have reported the following. Oscar Lin: Consultant for Hologic and Jansen. Marilyn M. Bui: Consultant and/or advisory board member of Visiopharm, Aiforia, and PathAI. Anil V. Parwani: Advisory board for PathPresenter, Consultant for PAIGE. Liron Pantanowitz: Consultant for Hamamatsu & AIxMed, advisory board for Ibex and NTP, co-founder of LeanAP Innovators &

Placenta AI. Zaibo Li: Consultant for PathAI; Advisory Board for Roche Diagnostics. All other authors have no financial relationship to disclose.

CRediT authorship contribution statement

David Kim: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michael J. Thrall:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Pamela Michelow:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Fernando C. Schmitt:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Philippe R. Vielh:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Conceptualization. **Momin T. Siddiqui:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Kaitlin E. Sundling:** Conceptualization, Data curation, Formal analysis, Investigation, Writing – review & editing. **Renu Virk:** Conceptualization, Data curation, Formal analysis, Investigation, Writing – review & editing. **Susan Alperstein:** Conceptualization, Data curation, Formal analysis, Investigation, Writing – review & editing. **Marilyn M. Bui:** Conceptualization, Data curation, Formal analysis, Investigation, Writing – review & editing. **Heather Chen-Yost:** Conceptualization, Data curation, Formal analysis, Investigation, Writing – review & editing. **Amber D. Donnelly:** Conceptualization, Data curation, Formal analysis, Investigation, Writing – review & editing. **Oscar Lin:** Conceptualization, Data curation, Formal analysis, Investigation, Writing – review & editing. **Xiaoying Liu:** Conceptualization, Data curation, Formal analysis, Investigation, Writing – review & editing. **Emilio Madrigal:** Conceptualization, Data curation, Formal analysis, Investigation, Writing – review & editing. **Maureen F. Zakowski:** Data curation, Formal analysis, Investigation, Writing – review & editing. **Anil V. Parwani:** Conceptualization, Data curation, Formal analysis, Investigation, Writing – review & editing. **Elizabeth Jenkins:** Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Resources, Writing – review & editing. **Liron Pantanowitz:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis. **Zaibo Li:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

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Supplementary data

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