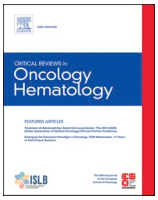
Critical Reviews in Oncology / Hematology 222 (2026) 105263

Contents lists available at ScienceDirect

Critical Reviews in Oncology / Hematology

journal homepage: www.elsevier.com/locate/critrevonc



Pathology in motion: Automation from specimen to report

Vincenzo L'Imperio [a], Angelo Paolo Dei Tos [b], Maurizio Carbone [a], Umberto Malapelle [c], Claudio Bellevicine [c], Giancarlo Troncone [c], Pasquale Pisapia [c], Stefano Marletta [d,e], Matteo Brunelli [f], Aldo Scarpa [f], Stefano Grassi [g], Giorgio Cazzaniga [a], Fabio Pagni [a], Albino Eccher [h,*]

[a] Department of Medicine and Surgery, Pathology, IRCCS Fondazione San Gerardo dei Tintori, University of Milano-Bicocca, Italy
[b] Surgical Pathology and Cytopathology Unit, Department of Medicine-DIMED, University of Padua School of Medicine, Padua, Italy
[c] Department of Public Health, University of Naples Federico II, Naples, Italy
[d] Department of Biomedical Science, Humanitas University, Milan, Italy
[e] Division of Pathology, Humanitas Istituto Clinico Catanese, Catania, Italy
[f] Department of Diagnostics and Public Health, Section of Pathology, University of Verona, Verona, Italy
[g] Department of Pathology, San Raffaele Hospital, Milan, Italy
[h] Department of Medical and Surgical Sciences for Children and Adults, University of Modena and Reggio Emilia, University Hospital of Modena, Modena, Italy

ARTICLE INFO

Keywords:
Digital pathology
Automation
Pathology workflow
Cutting
Embedding

ABSTRACT

Pathology laboratories are increasingly strained by rising diagnostic demand, greater case complexity, and limited staffing. Manual, analog workflows continue to dominate, yet they are time-consuming, prone to error, and contribute to inefficiency and staff burnout. Automation has been proposed as a strategy to address these challenges and improve sustainability. We reviewed current automation solutions available for key phases of the pathology workflow, including grossing, labeling, processing, embedding, microtomy, and archiving. Data were compared against estimates from traditional manual workflows to highlight potential gains in efficiency, accuracy, and traceability. Automation was shown to improve both efficiency and reliability across multiple stages. Advanced processing systems, such as microwave-assisted and ultrasound-based instruments, allowed faster turnaround with better tissue preservation. Embedding automation reduced operator time by more than 50%, sparing up to 40 working days annually. Automated microtomes cut sectioning times nearly in half, saving up to 470 h per year, though adoption remains limited by high cost and a slow return on investment. Automated archival systems decreased manual handling by approximately 550 h per year, while also ensuring controlled storage conditions and improved sample tracking. Automation offers clear benefits for standardization, efficiency, and diagnostic safety, while allowing staff to focus on higher-value activities. However, high implementation costs, infrastructural demands, and incomplete coverage of specialized needs remain barriers. Despite these limitations, automation represents a critical pathway toward resilient and future-ready pathology services.

1. Introduction

In recent years pathology laboratories are facing a growing crisis marked by a shortage of qualified personnel and an increasing workload (Walsh and Orsi, 2024). The number of pathology requests continues to rise steadily (estimated +5–10% yearly), driven by demographic trends, expanded screening programs, and advances in diagnostic and therapeutic strategies (Bray et al. 2024). At the same time, the complexity of individual cases has significantly increased, requiring progressively more time, attention, and expertise for each diagnostic report (Bonert et al. 2021). This growing demand, combined with limited human resources, has led to mounting pressure on pathology staff. The shortage affects not only medical pathologists but also laboratory technicians creating critical bottlenecks in routine workflows (Halstead and Sautter, 2023). Over time, these conditions contribute to demoralization, decreased job satisfaction, and a heightened risk of burnout among professionals, ultimately impacting the quality of patient care. One of the reasons for this frustration probably relies on the intrinsic nature of the traditional analog pathology workflow, mainly dominated by the manual handling of the specimen throughout all the phases, which is on

* Corresponding author.
E-mail address: albino.eccher@unimore.it (A. Eccher).

https://doi.org/10.1016/j.critrevonc.2026.105263
Received 11 November 2025; Received in revised form 2 March 2026; Accepted 5 March 2026
Available online 8 March 2026

one hand time-consuming and on the other hand prone to errors. It has been estimated that the rate of non-conformances due to manual handling during the pre-analytical phase is around 0.44%, with key error-prone steps during labelling (35%), grossing (28%), cutting (23%) and embedding (4.5%) phases (Morelli et al. 2013), as confirmed by our own data (Fig. 1). The introduction of automation technology may alleviate such constraints, allowing us to face growing workload with the current available workforce without sacrificing patient care. Automating key processes such as embedding, sectioning, and archiving can enhance the overall standardization of laboratory workflows, improving traceability and minimizing the risk of human error (Munari et al. 2024). In addition, by automating repetitive tasks, technical staff can be moved to more added-value activities. Moreover, the introduction of automation in pathology laboratory processes can facilitate the compliance with international standards (e.g. ISO 15189) and the different inspection programs to which laboratories are subject (e.g. from College of American Pathologists, CAP). In particular, the adoption of labeling, tracking and documentation of all pre and post-analytical phases which are the most critical of the workflow supports compliance with traceability, risk management and quality system requirements. Here we report the landscape of automation solutions for the pathology lab workflow currently available in the market, discussing the potentialities and current challenges to be faced for their implementation, stressing the importance of key performance indicators extracted from the routine analog manual pathology workflow for comparison.

2. Welcome to the automation world: entering the grossing room

The grossing phase is pivotal for diagnostic accuracy and patient safety in pathology. Errors at this stage, such as incomplete descriptions, mislabeling, or inadequate sampling, cannot be corrected later and may permanently compromise diagnosis and clinical management (Varma et al. 2024). Analog workflows, which depend on manual transcription, are prone to variable quality, processing delays, and inconsistent documentation. The lack of standardized graphical records often results in the loss of critical visual information, limiting retrospective review and teaching. Similarly, the absence of integrated digital photography and structured metadata complicates image retrieval and case correlation (Madrigal and Long Phi Le., 2021; Leong et al. 2000). Integrating digital cameras into grossing hoods has been shown to improve efficiency, accuracy, and educational value. Studies confirm the benefits of both consumer-grade and specialized systems for routine specimen documentation (Horn et al. 2014; Park et al. 2003; Hamza and Reddy, 2004). Several commercial solutions are available (Table 1a), ranging from high-end integrated platforms with LIS and DICOM compatibility, suited to large laboratories, to mid-range systems that balance cost and performance, and affordable options with limited LIS integration. Pre-analytic deficiencies, such as incomplete or illegible handwritten data, missing clinical information, and errors in specimen accessioning,

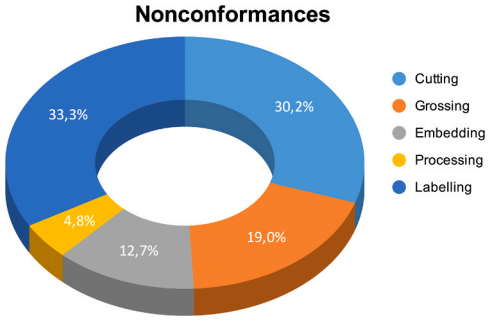


Fig. 1. Rate of pre-analytical nonconformances (0.66% yearly overall) registered within the pathology laboratory divided per workflow step.

are frequent sources of diagnostic delay and increased healthcare costs (Truong et al. 2024). Handwritten cassette labeling, in particular, is error-prone and carries risks of misidentification and specimen mix-ups. Such errors may assign slides to the wrong patient, leading to unnecessary procedures, delayed diagnoses, and potential patient harm (Layfield and Anderson, 2010; Brown et al. 2015). Professional guidelines from the College of American Pathologists and the National Society for Histotechnology emphasize that manual labeling of blocks and slides heightens vulnerability to misidentification, underscoring the need for unambiguous identification to prevent serious errors (Brown et al. 2015). Automated cassette printers, especially those integrated with barcode technology, markedly reduce misidentification and improve efficiency. In parallel with the reduction of errors, the introduction of such automation systems further contribute to render a structured and auditable traceability framework in line with the international standards applicable to pathology laboratories (e.g. ISO 15189) and helping with inspection programs (e.g. CAP). Reported benefits include up to a 95% decrease in slide misidentification defects and a 125% increase in microtomy throughput (Zarbo et al. 2009). Current technologies employ inkjet, thermal transfer, or laser printing systems (Table 1b), ranging from compact entry-level models to high-throughput, multi-hopper devices offering improved resolution and durability.

3. Cassettes to blocks: automating the journey

The processing phase is predominantly managed by automated instruments in most laboratories. However, these systems generally operate on fixed cycles and reagent schedules, limiting the ability to adjust parameters such as dehydration, clearing, and infiltration to match specimen size, composition, or sensitivity (Aziz and Zeman-Pocrnich, 2022). This rigidity can lead to suboptimal preservation, morphological artifacts, and compromised antigenicity, particularly affecting downstream molecular and immunohistochemical analyses (Bass et al. 2014; Durán et al. 2011). Manual and semi-automated systems likewise lack flexibility, offering limited capacity to switch between alternative reagents or embedding media, such as low-melting waxes or resins, required for specialized applications or preservation of labile molecular targets (Mazzoni and Quagio-Grassiotto, 2021). Reliance on conventional solvents like xylene and paraffin may also introduce technical artifacts and restrict histological quality compared with newer approaches that preserve morphology and molecular integrity more effectively. Innovations such as microwave-assisted tissue processors and rapid ultrasound-based systems have demonstrated significant reductions in turnaround times, with same-day reporting increasing from under 1% to nearly 80% for routine surgical specimens (Morales et al. 2004; Munkholm et al. 2008; Leong and Price, 2004; Morales et al. 2002, 2008). Current commercial solutions (Table 2a) range from compact, entry-level instruments suitable for smaller laboratories to high-capacity platforms designed for large centers, including hybrid systems that integrate processing and embedding within a single streamlined workflow. Finishing the processing phase, embedding is considered one of the slowest phases in the histopathology workflow, with still limited data on its actual impact on staff time (Munari et al. 2024). Previous works already estimated the efficiency of automated embedding solutions as compared to the "standard" manual methods, with up to 80% of time spared for technicians and an estimated increase to 840 blocks vs the 221 that can be obtained manually per day (Sarah E Wall, 2022). Based on unpublished authors' data, the average time required for embedding biopsies and surgical specimens is around 41.6 and 34.2 s, respectively, with higher variability observed in biopsies (range 20–82 s) compared to surgical specimens (range 16–67 s). Expanding these estimates to a laboratory with a 45,000 blocks/year workload, it can be assumed a required manual embedding time of approximately 474 h per year, equivalent to about 59 full working days (8 h/day) dedicated solely to embedding activities. These findings confirm that manual embedding consumes a

Table 1
Commercially available solutions to promote automation in the grossing rooms (hood cameras in a and cassette printers in b).

a.

System / Vendor	Camera Type / Resolution	Illumination	Integration & Connectivity	Key Features	Strengths	Notes / Limitations
MacroPATH (Milestone)	High-resolution digital macro camera, 20 MP	Built-In, Dimmable LED Lights	USB, Ethernet, LIS integration	- Mounted in grossing station or standalone - Foot pedal capture - Barcode integration - Real-time annotations	- Standardizes macroscopic documentation - High-quality images for reports & teaching - Hands-free operation - Potential extended tracking to other Milestone units	-
VisionTek Gross Imaging System (Sakura)	1080 HD	Integrated lightbox	USB, LAN	- Compact imaging station - Real-time annotation - Auto focus/ auto exposure - Supports consultation	- Fits in smaller labs - Supports teaching & QA	Resolution lower than Milestone systems
PathCamHR (Mopec)	HD camera, 24 MP 10 resolution settings (6000 ×4000 pixels)	Surgical Lights	USB, LIS connectivity	- Custom Foot Pedal and Voice Commands - Compatible with Dragon voice-to-text software and 3rd party videoconferencing and editing - Barcode integration	- Standard word nder dictionary (Auto-completes medical terms when typing) - Background Editing Tool	Typicall integrated within the Maestro Encore grossing station
PATHpix XLS (Virtus Imaging)	HD camera, 5 MP, 2448 × 2048 pixel resolution	Optimized LED Lighting	camera	- Barcode & Foot Controls - Motorized Zoom Lens	- Remote Screencasting	Lower resolution as compared to the other solutions
PathStand Imaging Station (SPOT Imaging)	20 MP	Built-in illumination	USB, LIS connectivity	- Adjustable camera stand for grossing - Barcode integration - Foot pedal - Real-time annotation - Remote consultation	- Handles routine and frozen specimens - Good teaching tool	Requires bench space; less integrated with hoods

b.

System / Vendor	Print Technology	Speed / Resolution	Capacity	Integration & Connectivity	Key Features	Strengths	Notes / Limitations
Leica IP C	Ink	~13 cassettes/ min (≈780/ hr), 360 dpi	6 hoppers (480 cassettes)	Ethernet, LIS	High-speed inkjet, solvent-resistant ink	- Very fast - Permanent ID with special ink - Flexible cassette handling	Requires Leica-approved cassettes & ink cartridges
Vega (Epredia/FA-TECH)	Laser	~5 s/ cassette (≈700/hr), 600 dpi	6 rotating hoppers	USB, Ethernet, LIS	High-resolution laser, solvent-proof	- No ink/ ribbons - Resistant to xylene, alcohol, acids -Handles multiple cassette types	Medium throughput vs other lasers
Nova (Epredia/FA-TECH)	Laser	~5 s/ cassette (≈700/hr), 600 dpi	4 hoppers (expandable)	USB, Ethernet, LIS	Compact version of Vega	- Same permanence as Vega - Lower entry cost - Expandable for lab growth	Less suited to high-volume labs
TCP Series (FA-TECH)	Laser	~4–5 s/ cassette (≈800–900/ hr), 2500 dpi	Multiple hoppers	USB, LAN, LIS	Non-contact, solvent-proof, high-res	- Permanent ID - High speed - No consumables	Often overlaps in branding with Nova/Vega series
EBMarker-160 (HealthSky)	Laser (IR)	≤ 3 s/ cassette (≤1200/hr), 2500 dpi	6 hoppers	USB, LIS/LIMS	Multi-hopper laser, non-contact printing	- High speed & resolution - Permanent marks - Supports multiple cassette types	Compatibility depends on cassette material (laser-absorbing)

(*continued on next page*)

Table 1 (*continued*)

b.

System / Vendor	Print Technology	Speed / Resolution	Capacity	Integration & Connectivity	Key Features	Strengths	Notes / Limitations
DTM TCP400/450 (DTM Medical)	Laser (UV)	~4 s/ cassette (≈900/hr), 2500 dpi	6 hoppers (75 each), 2 outputs	USB & Ethernet, PC + scanner	Permanent high-res marking, logos, barcodes	- Solvent-proof, no consumables - High throughput	Higher upfront cost; requires laser safety measures
Primera Signature Cassette Printer (DTM Medical)	Thermal transfer	~6–8 s/ cassette (≈450/hr), 300 dpi	4 hoppers (40 each)	USB & Ethernet, LIS via PTLab	Direct-to-cassette, color/ mono, chemical-resistant	- Flexible, compact - Multiple cassette types at once - Reduces errors & handwriting	Lower throughput vs laser; ribbons required
PrintMate AS (Epredia)	Thermal transfer	~6 s/ cassette (≈600/hr), 600 dpi	Up to 6 hoppers (50 each)	USB, LIS/LIMS	Compact, direct printing at grossing station	- Reliable barcode printing - Supports multiple cassette types - Small footprint	Thermal print less durable in harsh chemicals
Tissue-Tek SmartWrite (Sakura)	Thermal transfer	~ 8 cassettes/ min (black) (~480/hr) ~ 5 cassettes/ min (solid colors) (~300/hr) ~ 10 cassettes/ min with manual feed (~600/hr), 300 dpi	9 hoppers, 4 with autoloader (40 each for the autoloader)	USB, LIS	Color/ mono, text, 1D&2D barcodes	- Compact - Autoloader reduce the need of manual feeding - Integrated software for customized template design, printer management and LIS integration	Ribbon consumables, low throughput, validated and optimized for proprietary consumables
CapMate+ / PiSmart Module (CellPath)	Thermal transfer	~5–6 s/ cassette (≈600/hr)	6 hoppers	USB & Ethernet	Entry-level, LIS compatible	- Cost-effective - Compact for smaller labs	Lower throughput vs laser; ribbons required

significant amount of human resources and justify the implementation of automated embedding systems (Table 2b). Moreover, the introduction of special molds suitable for orientation directly during grossing may prevent potential errors during embedding that may result in loss of materials and delays in diagnosis. The implementation of these automatic embedding solutions could cut operator involvement by an estimated 50–70%, potentially saving 25–40 working days annually, while also reducing variability and improving standardization of block preparation. However, the introduction of such solutions may be challenging, requiring a personnel education program to adjust the grossing phase since some of these instruments require specific consumables (e.g. molds) which if not appropriately employed may cause embedding artifacts (Goldberg et al. 2015), while representing a further investment required for setting up the facility.

4. Cutting down times with automated microtomes

Microtomy is a critical step in the pathology workflow and often represents a bottleneck in slide preparation. Cutting times average 71.5 (± 42.1) seconds per biopsy block and 42.3 (± 20.5) seconds per surgical specimen block, with occasional outliers exceeding 120 s. In a laboratory processing 90,000 slides annually, this corresponds to approximately 1697,2 h per year, or 213 full working days (8 h/day). These figures highlight the substantial time burden of manual sectioning. Automated microtomes, which can standardize sectioning times to 25–30 s per slide, have the potential to reduce variability and save an estimated 315–470 h annually (40–59 working days). Recently introduced systems extend automation even further, handling blocks and slides from barcode reading through to slide labeling after section deposition (Table 3a). These platforms could significantly streamline what remains one of the most manual phases of histology. A major challenge, however, is the high cost of implementation. Such investments are often prohibitive for small and medium-sized laboratories, while larger institutions must account for a relatively slow return on investment, estimated at around five years (Ciancia et al. 2024). In laboratories with manual microtomy still in place, the minimum requirement for preserving the traceability of the sample should be the introduction of slide printers (Table 3b), which can allow best durability thanks to the laser technology or flexibility and cost-effectiveness in case of thermal transfer methods, ensuring the integration with the LIS and adequately fast throughput while avoiding manual transcription/interpretation errors. After the cutting phase, the automation should ideally cover the staining phase of both routine histology (for hematoxylin and eosin), special histochemical stains and immunohistochemistry (IHC). The implementation of such instruments would ensure adequate and precise control of incubation times, minimization of technical artifacts of this phase with standardization of the final product, which is key in the digitization era. Moreover, the integration of these instruments with the LIS allows a further reduction of errors, a better monitoring of the different steps of the sample with continuous

Table 2
Commercially available solutions to promote automation during the processing (a)/embedding (b) phases.

a.

System / Vendor	Type	Capacity	Processing Modes	Integration & Connectivity	Key Features	Strengths	Notes / Limitations
ASP6025 S (Leica)	Fully enclosed vacuum processor	~300 cassettes	Conventional	LIS/LIMS connectivity	Magnetic stirring, reagent density monitoring, advanced safety	- Reliable infiltration - Strong reagent control - Enhanced safety sensors	Mid-capacity; slower than hybrid systems
HistoCore Pegasus (Leica)	Single-retort processor	Up to 400 cassettes	Conventional	LIS-ready	Parallel protocols in one retort	- Compact - Reliable workflow automation	Single retort limits urgent/routine overlap
HistoCore Pegasus Plus (Leica)	Dual-retort processor	Up to 400 cassettes	Conventional (parallel)	LIS/LIMS, track & trace	Two independent retorts, track & trace	- Process urgent + routine simultaneously	More costly; larger footprint
Peloris 3 (Leica)	Dual-retort processor	Up to 600 (2 ×300)	Conventional & rapid	LIS/DICOM connectivity	Two parallel workflows, energy-efficient	- Very high capacity - Flexible for large labs	Premium cost; requires large space
Excelsior AS (Thermo Scientific)	Enclosed vacuum processor	~300 cassettes	Conventional & rapid	LIS-ready	Reagent Management System, vacuum/pressure cycles	- Trusted, balanced performance - Good reagent economy	Mid-capacity; less flexible than dual-retort
Tissue-Tek VIP® 6 AI (Sakura)	Vacuum infiltration	up to 300 cassettes	Conventional	LIS connectivity	AI-optimized protocols, tissue protection	- Proven Sakura reliability - Consistent results	Requires AI training; larger footprint
Tissue-Tek Xpress x120 (Sakura)	Continuous rapid tissue processor (microwave)	~120 cassettes (continuous flow)	1–2.5 h rapid protocols	LIS connectivity	Microwave + vacuum hybrid, continuous loading	- Very fast TAT (~1 h) - STAT-friendly	Lower throughput for bulk routine cases
LOGOS EVO (Milestone)	Hybrid microwave + conventional	Up to 210 cassettes	Conventional & rapid	LIS/LIMS, DICOM-ready	Dual-run capacity, microwave boost	- Flexible protocols - Faster turnaround - Eco-friendly	Lower max capacity vs large processors
LOGOS One (Milestone)	Hybrid microwave + conventional	Up to 210 cassettes	Routine & rapid	LIS-ready	Compact, user-friendly	- Eco-friendly - Ideal mid-size labs	Limited for very high-volume labs
Synergy (Milestone)	One-step processor + embedding	N/A	Combined processing & embedding	LIS-ready	Eliminates separate embedding step	- Saves technician time - Streamlined workflow	Conceptually different, less conventional
Magnus (Milestone)	High-capacity tissue processor	Up to 720 cassettes	Conventional	LIS-ready	Massive cassette basket, advanced safety	- Designed for mega-labs - Very high throughput	Very large footprint; suited for central labs

b.

System / Vendor	Type / Automation Level	Throughput / Capacity	Integration & Connectivity	Key Features / Automation Steps	Strengths	Notes / Limitations
Tissue-Tek AutoTEC a120 (Sakura)	Fully automated embedding	Up to 120 paraffin cassettes/hour	LIS interface via barcode reader built-in	Continuous loading & output, SMARTair™ to remove excess paraffin, cassette barcode reading, eliminates block scraping	- Frees operator from manual embedding tasks - Reduces orientation errors - Standardized block quality & consistency - Continuous throughput to feed microtomy	Only works with Sakura's Paraform® cassette system; availability limited in some markets
FlexPath™ Blox (Inpeco)	Automated embedding module (automation-assisted)	Up to ~120 blocks/hour	Full traceability via FlexPath Trace; integrates with Inpeco's automation chain	Automates non-technical steps: block detachment, automated wax dispensing, mold reloading, case sorting, sample management, interface with FlexPath Move for block transport	- Operator focuses only on tissue orientation - Reduced paraffin waste - Traceability & automation across embedding → microtomy chain - Open compatibility with standard cassettes & processor baskets	It is an embedding module (requires upstream processor and downstream handling)
Synergy (Milestone)	Integrated process + embedding (one-step)	N/A	Intended to link processing and embedding in one workflow	Eliminates separate embedding step by combining processing & embedding module in one continuous system	- Minimizes handoffs - Potentially shorter TAT by merging embedding into processing	Lack of full specifications disclosure

Table 3
Commercially available solutions to promote automation during the cutting phase (automatic microtomes in a and slide printers in b).

a.

System / Vendor	Automation Scope	Capacity / Throughput	Key Features & Workflow Steps	Integration & Connectivity	Strengths	Notes / Limitations
AS-410M (Axlab)	Walk-away full automation (block → slide)	Up to 96 paraffin blocks → ~400 slides in a run (4–6 h)	- Automated block feeding - Automatic blade replacement - Block surface measurement & angle adjustment - Slide mounting, drying, registration - Residue vacuuming, barcode reading and slide printing	LIS / barcode connectivity; cassette barcode scanned; slide printing tied to block ID	- High consistency and reduction of manual load - Suitable for digital pathology (scan-ready slides) - Already > 100 installations globally	- Full automation mostly for "routine" block types; certain blocks (nets, unusual embedding) may require special handling - Throughput is finite (4–6 h per run) so planning is crucial
SectionStar (Clarapath)	Automated microtomy + trimming + transfer	Uses "72-block run modes" (various modes: trimming only, sectioning, full block-to-slide)	- Dual microtomes: separate trimming and sectioning units for batch workflow - Automatic blade replacement via blade-mark detection algorithm - Just-in-time barcode printing: block scanned, matching barcode printed on slide - Web-based UI / Histostation repository for traceability, remote operation ("Telehistology")	Full chain-of-custody via barcode matching; connectivity with LIS; tracking and trace via Histostation data repository	- High flexibility in run modes (trim-only, section-only, full) - Blade change automation improves throughput and lowers error risk - Remote operation capability reduces local staffing needs	- The system is relatively new; fewer independent publications on large-scale performance - Complexity of managing dual microtomes may require more rigorous maintenance - Real-world throughput (slides/hour) publicly less detailed
Robotome RTM30 (Morphle Labs)	Fully robotic microtomy + section pickup / transfer	Approx 100 slides/hour per Robotome	- Robotic arms for sectioning, facing, chilling, and section pickup / transfer to slide - Continuous blade switching / adaptive blade shifting based on quality metrics - Block chilling, surface detection, slide-block barcode matching and QC scan post pickup - Water-based section transport & pickup to minimize cross contamination / floaters	Slide-to-block barcode traceability; LIMS integration (custom, bidirectional) as part of deployment	- End-to-end automation including section pickup is a strong differentiator - High consistency, minimal intervention ideally - Designed for all kinds of blocks (soft to hard)	- Being relatively novel, fewer published case studies in clinical labs - Throughput is moderate (100 slides/h) so may require multiple units for high volume labs - Physical footprint, maintenance, calibration demands may be substantial

b.

System / Vendor	Print Technology	Speed / Resolution	Capacity	Integration & Connectivity	Key Features	Strengths	Notes / Limitations
HealthSky eMarker (11A-S100)	Laser (IR/UV)	≤ 4 s/slide (~15/min), 2500 dpi	Input: 100	USB, LIS/LIMS/HIS	Non-contact laser printing, solvent-proof	Permanent, durable print	Higher upfront cost; larger unit
DTM SP200 Dual-Hopper (DTM Medical)	Laser (UV)	Up to 15 slides/min, 2500 dpi	2 × 100 input, 2 × 20 output	USB & Ethernet, stand-alone PC + scanner	High-resolution, solvent-resistant, durable print	Permanent labeling, LIS ready	Higher cost, larger footprint
Primera Signature Classic (DTM Medical)	Thermal transfer	Up to 10 slides/min, 300 dpi	Input: 100, Output: 15	USB only, LIS via PTLab	Compact, cost-effective	Entry-level, reliable direct-to-slide	No Ethernet, fewer features
Epredia SlideMate Pro	Thermal transfer	4–5 s/slide (~12–15/min), 300 dpi	Dual hoppers + manual feed	USB & Ethernet, LIS/LIMS integration	- Intelligent Slide Selection- Dual hopper + manual feed for special slides - User login & sample tracking - Compact, fits next to microtome	- Reduces misidentification risk at cutting - Handles multiple slide types without reload - Saves bench space with small footprint - Supports traceability with login & audit trail	Throughput suitable for mid-size labs; durability vs laser printers should be assessed
ESPO II Slide Printer	Thermal transfer	20 slides/min, 300 dpi	2 magazines (100 slides each) + manual front loading; output 20–50	USB, LAN, WLAN; LIS/LIMS connectivity	- Dual magazines for multiple slide types - Manual loading for slides with tissue - Prints text, 1D/2D barcodes - Solvent-resistant printing	- High throughput, suitable for large labs - Flexible handling of routine - Strong LIS integration options - Chemical resistance ensures durability	Needs regular maintenance; dual magazine requires proper LIS configuration

(*continued on next page*)

Table 3 (*continued*)

b. System / Vendor	Print Technology	Speed / Resolution	Capacity	Integration & Connectivity	Key Features	Strengths	Notes / Limitations
Leica HistoCore PERMA S	Thermal transfer	up to 9 slides/min (mono) 5/min (color), 300 dpi	Input ~100	USB, LIS connectivity	Prints directly at microtome, uses PERMASLIDE slides	Prevents ID errors at cutting stage	Proprietary slides; limited flexibility
Sakura Tissue-Tek SmartWrite	Thermal transfer	9 slides/min (mono), 5/min (color), 300 dpi	Input: 100, Output: 15	USB, LIS	Supports text, barcodes, graphics; 8 solid colors	Smudge-proof, chemical-resistant, compact	Speed lower in color; ribbons required
CellPath PiSmart	Thermal transfer	3–5 s/slide (~12–20/min), 300 dpi	Single hopper (Pismart Slide printer) or two hoppers (Pismart Twin Hopper)	Ethernet, USB, LIS	On-demand printing, barcode scanner, small footprint	Fast, quiet, good LIS integration	Thermal ribbons needed
Primera Signature EVO (DTM Medical)	Thermal transfer	Up to 10 slides/min, 300 dpi	Input: 100, Output: 15	USB & Ethernet, LIS via PTLab	Full-color printing, EVO SlideSeparator™, compact footprint	Eliminates handwriting, chemical/UV resistant, flexible placement	Slower with color (5/min); ribbons required
CellPath ESPO	Thermal transfer	~3 s/slide (~20/min), 300 dpi	Dual magazines (100 slides each)	USB, LAN, WiFi	Touch panel, dual-slide magazine, solvent-resistant print	Flexible, fast, supports multiple slide types	LIS connectivity varies by lab

traceability of the phases.

5. Lost and found: automation in the pathology archives

Archival operations are a frequently underestimated component of the pathology workflow. Although regulatory guidelines require paraffin-embedded tissue blocks to be stored under controlled environmental conditions, in practice they are often kept in facilities with inadequate temperature and humidity regulation, risking degradation and compromising the reliability of ancillary testing (Xie et al. 2011). Storage and retrieval processes remain largely manual, relying on progressive alphanumeric numbering schemes that are vulnerable to misplacement and, at times, irreversible loss of material. These tasks also consume substantial staff time. On average, manual handling requires 6.5 ± 2.4 s per item (approximately 35.7 ± 10.8 s per case), corresponding to an annual workload of approximately 243 h (about 32 working days) devoted exclusively to manual archive management (as estimated in a laboratory with a workload of 25000 cases and 135000 items to be archived/retrieved). Automated systems, by contrast, complete each archiving cycle in about 31 s per item. Consequently, the time consumed by the system represents machine time rather than personnel time, allowing the operator to be reassigned to other laboratory duties. This translates into a potential saving that can range from + 0.12 to + 0.47 full time equivalent (FTE) per year depending on the size of the pathology laboratory (Fig. 2), while also eliminating the variability inherent to manual retrieval and ensuring higher process standardization and traceability. Automated storage solutions (Table 4) can both ensure optimal environmental conditions and improve specimen tracking, thereby enhancing sample integrity and overall laboratory efficiency. Depending on the system, they may provide simple traceability functions or fully integrated archiving and retrieval workflows. Many platforms are designed to interface with existing infrastructure, reducing implementation costs, or can be deployed as modular units to enhance safety and efficiency. Nevertheless, the adoption of automated archival systems presents challenges. High upfront investment, adaptation of laboratory workflows, and infrastructural requirements—such as machine-readable barcodes, standardized block dimensions, LIS integration, and lean laboratory design—must be addressed for successful implementation. In addition, certain needs remain unmet, including solutions for molecular specimens and macroblocks/slides, representing important directions for future development in precision pathology. Finally, the rising production of digital slides within our laboratories is creating new challenges in the storage/archival phase.

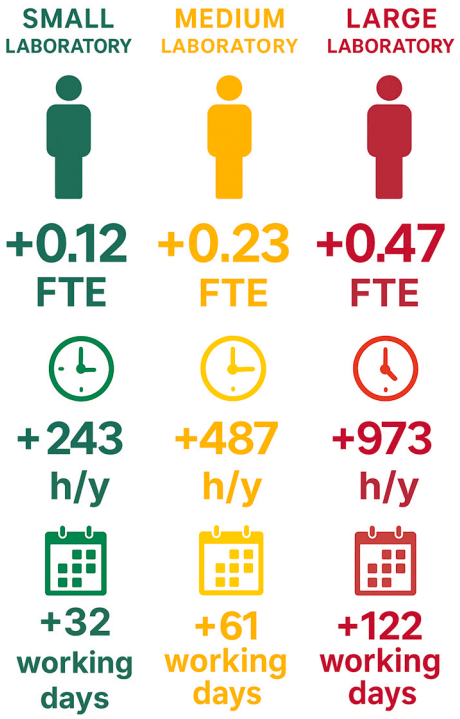


Fig. 2. Estimation of the different Full Time Equivalent (FTE) for the manual archival/retrieval of FFPE blocks and glass slides based on the assessment on differently sized laboratories. A small laboratory is defined as having 25000 cases and 135000 items (blocks/glass slides), a medium lab as having 50000 cases and 270000 items and a large lab having 100000 cases and 540000 items.

The minimum retention policies, the accessibility periods (cold vs hot storages), the on-premise local vs cloud-based solutions are some of the discussion points currently debated in the community, which further impact on the investments on archival/storage.

6. The vision of pathology automation

The automation solutions here largely represent currently existing solutions that can be implemented within the conventional pathology laboratory workflow, mainly in a single phase/compartment fashion.

Table 4
Commercially available solutions to promote automation in the archival phase.

System / Vendor	Storage Type	Integration & Connectivity	Key Features	Strengths	Notes / Limitations
FlexPath™ Store (Inpeco)	Blocks	Fully integrated with FlexPath Move (pneumatic transport), embedding & microtomy; LIS/HIS connectivity	- Robotic storage & retrieval - > 22,000 block capacity - RFID/QR-coded racks - Direct workflow automation	- End-to-end automation from embedding to archiving - Full traceability & chain-of-custody - Reduces manual workload, prevents misplacement	Requires full integration with other FlexPath modules (investment-heavy)
PathArchiv (SPOT Imaging)	Blocks and slides	Web-based software, LAN, minimal IT setup	- Uses standard archive boxes (no proprietary cabinets) - Very high density (25–200% more than competitors) - Automated barcode scanning - Handles "exceptional" cases via ExTrak	- Low infrastructure costs - Prevents lost/misfiled samples	Less integrated with robotic lab automation; more focused on cost-efficient storage
IstoTech (ICAM)	Blocks and slides	ICON web-based software, LIS/HIS connectivity	- Scales from 400k to 15 M slides - Barcode/QR-coded trays - Light Picking retrieval - Fire/dust/humidity protection - Ergonomic trays (<1.5 kg)	- Maximum storage density - Safe handling & reduced errors - Strong physical security & sample protection	Large-scale solution; better suited for central archives than small labs
smartCABINET (Logibiotech)	Blocks, slides, macro and vials	samAPP software, LIS connectivity, WiFi, robotic helper (finderFLEX)	- Modular system (smartCABINET + clientCABINETs) - Rack system: slRACK, bcRACK, vlRACK etc. - Robotic arm for scanning & retrieval - Supports multiple sample formats	- High modularity & scalability - Pick-to-light reduces human error - Traceability across different sample types - Supports standard containers	Detailed throughput/retrieval benchmarks less openly available; newer solution with fewer peer-reviewed validations
Dreampath (Fina & Crystal)	Blocks (Fina) and slides (Crystal)	LIS/LIMS interfacing; closed-loop	- Block trays scanned, photographed, barcoded - Retrieval via pick list & PDA scan-out - Non-sequential storage - Crystal module for slides - Drawer variants for block categories	- Significant reduction in retrieval/archiving time - Enhanced traceability & security (no visible labels on cabinets) - Proven deployment in major labs (e.g. Erasmus MC)	Slide module newer (less published validation) Integration depth varies by lab deployment

Envisioning a more seamless integration of automation solutions in our laboratories, the future may bring us unified digital workflows linking tissue processing, sectioning, staining and immunohistochemical/molecular analysis minimizing human intervention and ensuring bidirectional LIS connectivity for real-time monitoring. The implementation of identification systems alternative to the currently used 1D or 2D barcodes (e.g. radio-frequency identification technologies, RFID) may allow contactless automated specimen identification and tracking from the sampling room to the archival step. These systems are based on solid-state tags instead of conventionally used printed labels, allowing batch-level tracking, automated inventory control and full chain-of-custody documentation, further strengthening operational efficiency and accreditation compliance. Finally, as a future perspective development, the full integration of the cytology workflows of our laboratories is desirable, since liquid-based preparations and cell block workflows are still at least partly manually managed and would significantly benefit from similar seamless automation solutions.

7. Critical view

This review addressed the timely topic related to the automation technologies applicable in the pathology laboratories, ranging a wide spectrum of applications from grossing to archiving. This has been performed in a workflow-centered and key performance indicator (KPI)-driven approach, providing readers useful references related to the available instruments for each step and application, while stressing the potential impact these implementations can have on the laboratories. From this effort, the operational, economic and organization impact of automation in pathology laboratories can be estimated through quantitative workload quantification and FTE calculation, supporting the novelty of technological advancements with concrete efficiency data. This is in line with the current need of our discipline, representing a strategic response to the increasing risk of workforce shortage and diagnostic complexity, with the parallel need to preserve the precious biological material of our patients. In line with the perspective of the authors, the present review aims to contribute to the currently available literature as a practical decision-making framework that may assist laboratory directors and policymakers in modernizing the pathology laboratories in motion.

8. Conclusions

Automation across the different workflow steps demonstrates clear advantages in efficiency, standardization, and traceability, with substantial time savings and improved patient safety (Fig. 3). Such improvement would also simplify adherence to accreditation systems and international standards. Looking forward, broader adoption will depend on balancing initial costs with long-term efficiency gains, while tailoring solutions to the scale and specific requirements of each laboratory. In this way, automation is poised to play a central role in building more resilient, efficient, and future-ready pathology services.

Authors contribution

VL, APDT, MC, and AE contributed to the conceptualization of the manuscript. VL and MC drafted the manuscript.UM, CB, GT, PP, SM, MB, AS, SG, GC, and FP critically revised the manuscript for important intellectual content. Supervision was provided by FP, AE, and APDT. All

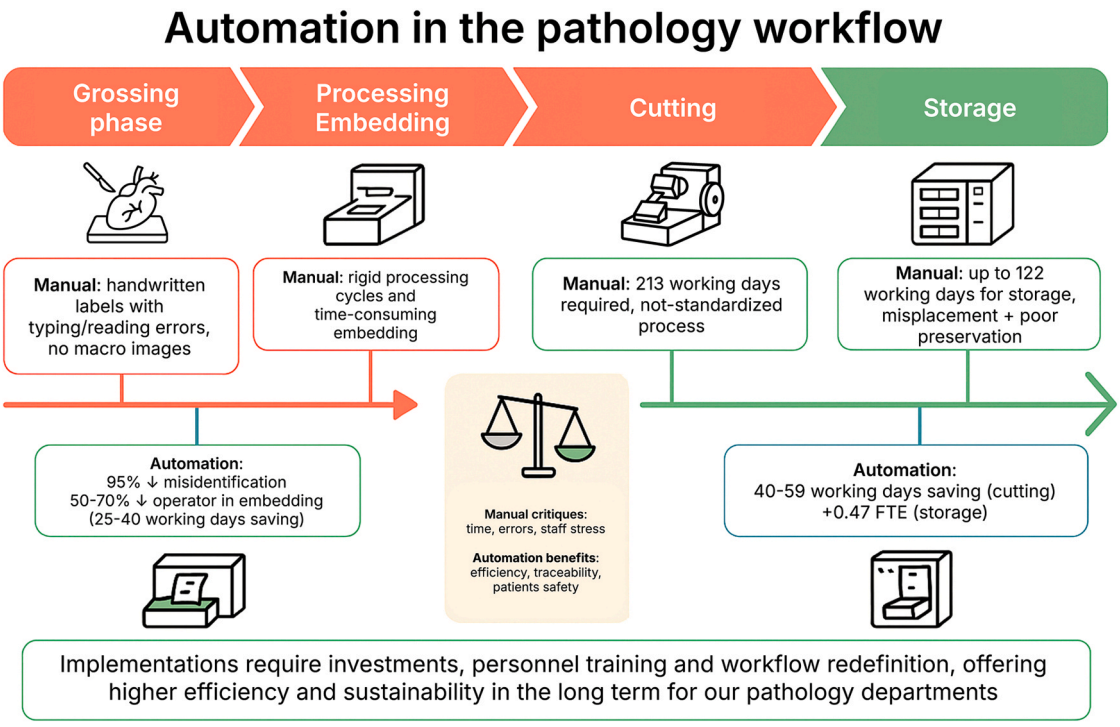


Fig. 3. Impact and challenges of the introduction of automation within the pathology laboratory workflow at each phase.

authors provided data for the drafting of the manuscript. All authors read and approved the final version of the manuscript.

Ethical statement

Not applicable.

Funding

None.

Declaration of Competing Interest

There are no competing financial interests concerning this work. The discussion of the possible automation tools and the evaluation of the current needs of the Pathology Laboratories were conducted independently by the authors without influence from the cited companies. Author 1 received honoraria as consultant and/or speaker bureau from Eli Lilly, Roche, Logibiotech, Menarini, Novartis unrelated to the current work. Author 4 received personal fees (as consultant and/or speaker bureau) from Amgen, Boehringer Ingelheim, Diaceutics, Eli Lilly, GSK, Merck, MSD, Roche, Thermo Fisher Scientific; and from AstraZeneca, Diatech, Hedera, Janssen, Novartis unrelated to the current work. Author 6 reports personal fees (as consultant and/or speaker bureau) from Boehringer Ingelheim, Roche, MSD, Pfizer, Eli Lilly, BMS, GSK, Menarini, AstraZeneca, Amgen and Bayer unrelated to the current work. Author 7 received personal fees (as consultant and/or speaker bureau) from Novartis unrelated to the current work. Author 13 received personal fees (as consultant and/or speaker bureau) from Amgen, Eli Lilly, GSK, Merck, MSD, Roche, AstraZeneca, Diatech, Janssen, Novartis, Logibiotech, Leica, Menarini, Sakura, Diapath, unrelated to the current work. Author 10, Author 11 and Author 14 received honoraria as consultant and/or speaker bureau from Logibiotech. The remaining authors do not have relevant disclosures. None of these activities were related to the current study.

Acknowledgments

None.

References

Aziz, Sarah J., Zeman-Pocrnich, Cady E., 2022. Tissue processing. Methods Mol. Biol. 2422, 47–63.
Bass, B., Paige, Kelly B., Engel, Sarah R., Greytak, Helen, M.Moore, 2014. "A review of preanalytical factors affecting molecular, protein, and morphological analysis of formalin-fixed, paraffin-embedded (FFPE) tissue: how well do you know your FFPE specimen?". Arch. Pathol. & Lab. Med. 138 (11), 1520–1530.
Bonert, Michael, Zafar, Uzma, Maung, Raymond, et al., 2021. Evolution of anatomic pathology workload from 2011 to 2019 assessed in a regional hospital laboratory via 574,093 pathology reports. PloS One 16 (6), e0253876.
Bray, Freddie, Laversanne, Mathieu, Sung, Hyuna, et al., 2024. Global Cancer Statistics 2022: GLOBOCAN estimates of incidence and mortality worldwide for 36 Cancers in 185 countries. CA A Cancer Journal Clinicians 74 (3), 229–263.
Brown, Richard W., Speranza, Vincent Della, Alvarez, Janice O., et al., 2015. Uniform labeling of blocks and slides in surgical pathology: guideline from the college of american pathologists pathology and laboratory quality center and the national society for histotechnology. Arch. Pathol. Lab. Med. 139 (12), 1515–1524.
Ciancia, Sabrina, Vannozzi, Lorenzo, Poliziani, Aliria, et al., 2024. Technologies for the Automation of Anatomic Pathology Processes: A Review. IEEE Trans. Med. Robot. Bionics 6 (3), 888–902.
Durán, Iván, Marí-Beffa, Manuel, Santamaría, Jesús A., Becerra, José, Santos-Ruiz, Leonor, 2011. Freeze Substitution Followed by Low Melting Point Wax Embedding Preserves Histomorphology and Allows Protein and mRNA Localization Techniques. Microsc. Res. Tech. 74 (5), 440–448.
Goldberg, Matthew S., Wetherington, Sarah J., Susa, Joseph S., Wickless, Scott C., Cockerell, Clay J., 2015. Characterization of Tissue and Slide Artifacts from Automated Embedding Systems. Am. J. Dermatopathol. 37 (11), 846–849.
Halstead, Diane C., Sautter, Robert L., 2023. A Literature Review on How We Can Address Medical Laboratory Scientist Staffing Shortages. Lab. Med. 54 (1), e31–e36.
Hamza, Sate H., Reddy, Vishnu V.B., 2004. Digital Image Acquisition Using a Consumer-Type Digital Camera in the Anatomic Pathology Setting. Adv. Anat. Pathol. 11 (2), 94–100.
Horn, Christopher L., DeKoning, Lawrence, Klonowski, Paul, Naugler, Christopher, 2014. Current Usage and Future Trends in Gross Digital Photography in Canada. BMC Med. Educ. 14 (January), 11.
Layfield, Lester J., Anderson, Gina M., 2010. Specimen labeling errors in surgical pathology: an 18-month experience. Am. J. Clin. Pathol. 134 (3), 466–470.
Leong, Anthony S.-Y., Price, David, 2004. Incorporation of microwave tissue processing into a routine pathology laboratory: impact on turnaround times and laboratory work patterns. Pathology 36 (4), 321–324.

Leong, A.S., Visinoni, F., Visinoni, C., Milios, J., 2000. An advanced digital image-capture computer system for gross specimens: a substitute for gross description. Pathology 32 (2), 131–135.
Madrigal, Emilio, Long Phi Le, 2021. Digital media archive for gross pathology images based on open-source tools and fast healthcare interoperability resources (FHIR). Mod. Pathol. Off. J. U. S. Can. Acad. Pathol. Inc. 34 (9), 1686–1695.
Mazzoni, Talita Sarah, Quagio-Grassiotto, Irani, 2021. Totum deparaffinization of biological samples and re-embedded in historesin for better diagnostic. Microsc. Res. Tech. 84 (7), 1362–1367.
Morales, Azorides R., Essenfeld, Harold, Essenfeld, Ervin, Maria, Duboue, Carmen, Vincek, Vladimir, Nadji, Mehrdad, 2002. Continuous-Specimen-Flow, High-Throughput, 1-Hour Tissue Processing. A System for Rapid Diagnostic Tissue Preparation. Arch. Pathol. & Lab. Med. 126 (5), 583–590.
Morales, Azorides R., Nadji, Mehrdad, Livingstone, Alan S., 2008. Rapid-Response, Molecular-Friendly Surgical Pathology: A Radical Departure from the Century-Old Routine Practice. J. Am. Coll. Surg. 207 (3), 320–325.
Morales, Azorides R., Nassiri, Mehdi, Kanhoush, Rima, Vincek, Vladimir, Nadji, Mehrdad, 2004. Experience with an Automated Microwave-Assisted Rapid Tissue Processing Method: Validation of Histologic Quality and Impact on the Timeliness of Diagnostic Surgical Pathology. Am. J. Clin. Pathol. 121 (4), 528–536.
Morelli, P., Porazzi, E., Ruspini, M., Restelli, U., Banfi, G., 2013. Analysis of errors in histology by root cause analysis: a pilot study. J. Prev. Med. Hyg. 54 (2), 90–96.
Munari, Enrico, Scarpa, Aldo, Cima, Luca, et al., 2024. Cutting-edge technology and automation in the pathology laboratory. Virchows Arch. Int. J. Pathol. 484 (4), 555–566.
Munkholm, Julie, Talman, Maj-Lis, Hasselager, Thomas, 2008. Implementation of a new rapid tissue processing method–advantages and challenges. Pathol. Res. Pract. 204 (12), 899–904.
Park, Rae-Woong, Joon-Hoe Eom, Byun, Ho-Yong, Park, Peom, Lee, Kyi-Beom, Joo, Hee-Jae, 2003. Automation of Gross Photography Using a Remote-Controlled Digital Camera System. Arch. Pathol. & Lab. Med. 127 (6), 726–731.
Truong, Tra, Roopchard, Preeya, Olkhov-Mitsel, Ekaterina, et al., 2024. Redefining and Capturing Pre-Analytic Deficiencies in an Anatomical Pathology Laboratory: A Quality Improvement Initiative. Virchows Arch. Int. J. Pathol. 484 (5), 743–751.
Varma, Murali, Collins, Laura C., Chetty, Runjan, et al., 2024. Macroscopic examination of pathology specimens: a critical reappraisal. J. Clin. Pathol. 77 (3), 164–168.
Wall, Sarah E., 2022. Automation in the histology laboratory: a comparison of manual verses automated processes. Int. J. Res. Acad. World 1 (8), 04–06.
Walsh, Elizabeth, Orsi, Nicolas M., 2024. The current troubled state of the global pathology workforce: a concise review. Diagn. Pathol. 19 (1), 163.
Xie, Ran, Chung, Joon-Yong, Ylaya, Kris, et al., 2011. Factors influencing the degradation of archival formalin-fixed paraffin-embedded tissue sections. J. Histochem. Cytochem. 59 (4), 356–365.
Zarbo, Richard J., Tuthill, J.Mark, D'Angelo, Rita, et al., 2009. The Henry Ford production system: reduction of surgical pathology in-process misidentification defects by bar code-specified work process standardization. Am. J. Clin. Pathol. 131 (4), 468–477.