

Cross-platform integration of robotic intraoperative ultrasound using system-agnostic drop-in probes: technical feasibility and workflow standardization

Chiara Innocenzi

Institut de Recherche contre les Cancers de l'Appareil Digestif

Federico Espínola

Institut de Recherche contre les Cancers de l'Appareil Digestif

Daichi Kitaguchi

Institut de Recherche contre les Cancers de l'Appareil Digestif

Matteo Pavone

Institut de Recherche contre les Cancers de l'Appareil Digestif

Antonello Forgione

Institut de Recherche contre les Cancers de l'Appareil Digestif

Jacques Marescau

Institut de Recherche contre les Cancers de l'Appareil Digestif

Mariano Eduardo Giménez

`mariano.gimenez@ircad.fr`

Institut de Recherche contre les Cancers de l'Appareil Digestif

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Abstract

Background

Intraoperative ultrasound can enhance real-time image guidance in minimally invasive surgery, but its integration into robotic workflows remains heterogeneous and frequently platform dependent. This study aimed to evaluate the feasibility and reproducibility of a standardized robotic intraoperative ultrasound (RIOUS) workflow using two system-agnostic drop-in probes across four multi-port robotic platforms and to generate video-based reference material for cross-platform training.

Methods

A technical feasibility study was conducted at IRCAD (Strasbourg, France) using the ARIETTA750VE ultrasound system, two drop-in linear probes (L43K and L51K), and an abdominal ultrasound phantom housed in a box trainer. Four robotic platforms were assessed: da Vinci Xi, Hugo RAS, Toumai, and hinotori. A standardized six-step protocol evaluated ultrasound machine positioning, safety checks, trocar configuration, probe insertion through an additional 12-mm surgical trocar, console image display, grasper selection and corresponding probes manipulation.

Results

The standardized workflow was successfully completed on all four platforms. Both probes were inserted and manipulated intracorporeally without probe detachment, cable entanglement or robotic arm interference. Real-time B-mode imaging was displayed at the console on every system through native split-view or picture-in-picture functions, or through an external auxiliary-display workflow. Platform-specific differences were observed in room layout, visualization modality and preferred grasper selection, but stable handling was achieved with standard robotic instruments on all systems. No relevant difference in clip grip stability between the two probe models was observed.

Conclusion

A reproducible, platform-agnostic RIOUS workflow is feasible across four architecturally distinct robotic systems. System-agnostic drop-in probes may facilitate cross-platform skill transfer, support structured training and represent a practical step toward collaborative tele-image-guided robotic surgery.

Introduction

Over the past decades, ultrasonography has become a cornerstone of real-time medical imaging owing to its safety profile, portability, cost-effectiveness, and broad diagnostic capabilities [1], features that also make it well suited for intraoperative use. Intraoperative ultrasound (IOUS) was first introduced in

urology in the 1960s [2], and is today integral to several surgical disciplines, including hepatobiliary, thoracic, retroperitoneal, and vascular surgery [3]. In minimally invasive surgery, IOUS enables lesion localization, characterization and staging, contributing to intraoperative decision-making and treatment personalization. In hepatobiliary-pancreatic and transplant surgery, IOUS provides real-time assessment of vascular patency and organ perfusion [3], and has recently emerged in gynecologic oncology for real-time characterization of adnexal masses [4], whereas ongoing clinical studies are investigating its role in the detection of lymph-node metastases [5–7]. The integration of advanced techniques, including Doppler, elastography and contrast-enhanced ultrasound can provide additional functional and tissue-characterization information [8].

As surgical practice evolved from open to laparoscopic and robot-assisted approaches, efforts to extend the advantages of IOUS to minimally invasive surgery led to the development of laparoscopic ultrasound (LUS) probes [9]. These devices are designed for introduction through standard laparoscopic ports and are characterized by a long rigid shaft, a flexible or steerable distal tip, and a small contact surface, and they can also support image-guided interventional procedures, such as needle guidance for biopsy, radiation and thermal ablation [10]. Augmented reality technologies applied to laparoscopic ultrasound showed to enhance accuracy and surgeon visual workflow efficiency across diverse minimally invasive surgical applications [11]. However, the rigid shaft constrains the range of achievable acquisition angles and makes intracorporeal manipulation technically demanding, a limitation that has contributed to the persistent underutilization of LUS in minimally invasive surgery.

These limitations have been partially addressed by the introduction of the “drop-in” probe design, that couples a long flexible cable to a compact, rounded transducer tip equipped with a small clip that can be grasped with standard laparoscopic or robotic instruments. Drop-in probes can be employed in open, laparoscopic, and robotic settings and, when manipulated with articulated robotic graspers, allow access to anatomical regions and acquisition angles that are difficult to achieve with rigid laparoscopic probes [12].

Over the past two decades, in the broader context of digital health and technological transformation, robotic surgery has experienced substantial growth [13], evolving toward a paradigm of computer-assisted surgery, in which advanced imaging and artificial intelligence, through computer vision, three-dimensional reconstruction, and virtual and augmented reality, are integrated to enhance intraoperative perception and decision-making [14]. Although these technologies hold the potential to improve the quality, efficacy, and safety of surgical procedures, their widespread clinical validation has not been formally established, due to unresolved challenges related to real-time image registration, tissue deformation, and the substantial computational resources required for reliable intraoperative image fusion [15]. In contrast, the clinical implementation of robotic intraoperative ultrasound (RIOUS) appears more readily achievable in the current technological landscape. The rapid acquisition of ultrasound skills by younger surgeons, together with the superior ergonomics, dexterity, and precision of robotic systems, are particularly relevant for ultrasound probe manipulation and fine spatial control [16, 17]. Technical feasibility studies have explored the integration of novel drop-in probes within robotic workflows,

demonstrating improved maneuverability and surgeon autonomy compared with rigid laparoscopic probes [18].

A remaining obstacle to the routine integration of RIOUS, however, could be the technical and economic burden of developing proprietary ultrasound probes tailored to each robotic platform, a constraint that limits the scalability and cross-institutional transferability of this technology. System-agnostic drop-in probes represent a possible solution, as their architecture makes them compatible with any robotic grasper capable of a stable precision grip, irrespective of the platform manufacturer. Accordingly, the aim of this study, performed at the IRCAD Research and Training Center (Strasbourg, France), was to evaluate the feasibility and practical reproducibility of a standardized RIOUS workflow using system-agnostic drop-in probes across four distinct multi-port robotic surgical systems, and to provide structured video-based reference material to support cross-platform skill transfer and broader adoption of intraoperative ultrasound in robotic surgical practice.

Materials and Methods

Study Design and Setting

This technical feasibility study was conducted at the IRCAD Research and Training Center (Strasbourg, France), a high-volume international center for minimally invasive and robotic surgery with simultaneous access to multiple robotic platforms. This study protocol was designed in accordance with SAGES (Society of American Gastrointestinal and Endoscopic Surgeons) Guidelines for the Introduction of New Technology and Techniques [19], using a structured six-step protocol to assess workflow reproducibility across platforms. No human participants or animal subjects were involved; all procedures were performed in a non-clinical, experimental setting, and no ethics committee approval was required.

Robotic Platforms

Four robotic surgical systems were evaluated, displayed in Fig. 1: (A) the da Vinci Xi (Intuitive Surgical, Sunnyvale, CA, USA); (B) the Hugo™ RAS (Medtronic, Minneapolis, USA); (C) the Toumai (MicroPort® MedBot™, Shanghai, China); and (D) the hinotori™ (Medicaroid Corporation, Kobe, Japan).

Ultrasound Equipment

All simulations were performed using the ARIETTA 750VE ultrasound system (FUJIFILM Healthcare Corporation, Tokyo, Japan), that supports real-time B-mode and Doppler imaging, contrast harmonic imaging (CHI), eFlow, and real-time tissue elastography (RTE). Two drop-in transducer models were tested: the L43K (frequency range 12–2 MHz, 26 mm footprint, linear array) and the L51K (frequency range 15–3 MHz, 13 mm footprint, linear array). Both probes feature a flexible cable, a clip designed for

standard robotic graspers, and full wrist articulation. The L43K is compatible with trocars with a diameter of 12 mm or more, and 10 mm or more for the L51K (*Table 1*).

Table 1

The primary specifications and features of the L43K and L51K drop-in probes are shown in the table.

	L43K	L51K
Transducer Type	Linear	Linear
Frequency	12 – 2 MHz	15 – 3 MHz
Footprint Length	26 mm	13 mm
Dimensions of Probe Head Width Height (incl. Fin)	12 mm 12 mm	8.5 mm 9.4 mm
Fin Location	Proximal side of the probe head	Approximately in the probe head center
Appearance		

Phantom Model

Simulations were performed using the US-3 IOUSFAN abdominal ultrasound phantom (Kyoto Kagaku Co., Ltd., Kyoto, Japan), a validated training model specifically designed for intraoperative open, laparoscopic and robotic ultrasound examination. The phantom is constructed from polyurethane elastomer and incorporates detailed anatomical representations of the upper abdomen, including the liver with segmental anatomy, portal and hepatic venous system, ligamentum teres and ligamentum venosum, biliary tract (gallbladder, cystic duct, intra- and extrahepatic bile ducts), pancreas with pancreatic duct, spleen, kidneys, and detailed vascular structures (aorta, vena cava, celiac artery and branches, portal vein, superior mesenteric vessels, and renal vessels). Simulated pathological findings include biliary stones, cysts, and solid tumors of the liver, pancreas, spleen, and kidneys, represented as both hypoechoic and hyperechoic lesions. The stomach and duodenum components are detachable, allowing variable scanning configurations of the bile duct and pancreas. The phantom measures approximately 30 × 38 × 17.5 cm (W×D×H) and was positioned inside a standard box trainer to allow trocar placement in realistic robotic port configurations. The phantom container was filled with water to ensure appropriate acoustic coupling and simulate intra-abdominal conditions.

Standardized Demonstration Protocol

A structured, six-step protocol was applied identically to all four platforms to ensure reproducibility and comparability. The protocol encompassed the following steps:

1. 1. Ultrasound machine placement: optimal positioning of the ultrasound machine relative to each robotic cart, console, and operative field was systematically determined and documented.
2. 2. Safety check: a pre-activation safety assessment was performed, including verification of probe attachment, cable routing without tension, absence of interference with robotic arms.
3. 3. Trocar configuration: port placement was tailored to the spatial requirements of each platform.
4. 4. Probe insertion: safe intracorporeal introduction under direct endoscopic vision was performed for both probe models through an additional 12-mm surgical trocar
5. 5. Console configuration and image display: the connectivity workflow and platform-specific image integration were documented for each system.
6. 6. Instrument selection and manipulation: multiple robotic graspers available on each platform were systematically evaluated to assess probe stability, range of motion, and fine manipulation capability.

Each step was recorded in its entirety, producing four independent video demonstrations, accessible in the Supplementary Materials.

Results

Ultrasound Machine Positioning

Optimal placement of the ultrasound machine varied according to the spatial footprint and arm architecture of each robotic platform. For platforms with a centralized monolithic boom (da Vinci Xi, hinotori, Toumai), a lateral position ipsilateral to the system tower was preferred to minimize cable tension and reduce the risk of robotic arm collision. For the modular, multi-arm architecture of the Hugo RAS, the ultrasound machine was positioned at the side of the operating table opposite to the primary operating arm cluster, allowing unobstructed cable routing. These configurations are illustrated in the supplementary video demonstrations.

Safety check

Prior to probe activation and manipulation, a structured pre-use safety assessment was systematically performed across all platforms. This step was considered mandatory in the docked robotic configuration to ensure a safe and immediate device retrieval in the event of an unplanned occurrence.

The assessment began with a visual inspection of the transducer surface, clip mechanism, and full cable length to exclude signs of physical damage, kinking, or insulation defects prior to insertion. Cable routing was then verified to ensure that the external portion of the cable exited the trocar site without tension,

looping, or contact with the robotic arms, thereby preventing unintended traction on the intrabdominal probe during arm movements. With the robot fully docked and all arms in operative position, the absence of cable entrapment, collision risk, or restricted arm mobility was confirmed before probe introduction. The ARIETTA 750VE was powered on, connected, and verified to be transmitting an active B-mode imaging signal prior to insertion, avoiding blind intracorporeal manipulation of an inactive device. Finally, the undocking sequence and emergency stop procedures specific to each platform were reviewed and confirmed accessible to the bedside assistant, ensuring that rapid probe removal remained feasible across all operative scenarios. No electrical safety testing was performed in this experimental setting, as all procedures were conducted on a phantom model outside a clinical environment. In a clinical operative context, formal electrical safety verification of the ultrasound system should be confirmed prior to each operative session, as well as the trocar seal competence, verifying that the 12-mm valve accommodated the probe cable without loss of pneumoperitoneum.

Trocar Placement and Probe Insertion

The drop-in probe was successfully inserted through a dedicated 12 mm accessory trocar in all four platforms without requiring modification of standard port configurations. Sharing the trocar with a robotic arm was not feasible on these platforms due to spatial constraints. Both the L43K and L51K probes were introduced without difficulty; the smaller footprint of the L51K (13 mm) provided an advantage in navigating confined anatomical regions within the phantom, while the L43K offered broader contact surface and superior image quality for larger structures. No probe detachment, cable entanglement, or unintended pressure events were recorded during any of the simulation sessions.

Console Integration and Image Display

Real-time ultrasound image integration at the surgeon's console was achieved on all four platforms, though through distinct modalities, as shown in Table 2.

The da Vinci Xi system features an ergonomic closed surgeon console equipped with a stereoscopic 3D high-definition viewer. It incorporates TilePro™, a native multi-input visualization module embedded within the surgeon console, enabling simultaneous display of supplementary image streams alongside the primary 3D operative field [13] (Fig. 2A). Compatible sources include real-time intraoperative ultrasound imaging, secondary endoscopic views, pre- or intraoperative radiological imaging, and three-dimensional anatomical reconstructions.

The Hugo™ RAS platform is built around an open surgeon console with a high-definition 3D passive display, designed to preserve situational awareness within the operating room environment [20]. The platform does not feature a native integrated visualization module. To achieve real-time intraoperative ultrasound integration, an external workflow was implemented using the Touch Surgery™ DS1 ecosystem (Medtronic) [21]. The ultrasound machine was connected to the Touch Surgery™ DS1 system, which transmitted the ultrasound signal via Bluetooth to a dedicated auxiliary monitor positioned adjacent to the surgeon console, enabling real-time visualization of the sonographic field without interrupting the

robotic workflow (Fig. 2B). Unlike the main console, the auxiliary monitor does not incorporate a gaze-tracking alignment system; however, positioning the screen immediately next to or above the main console prevented unintended console locking when the surgeon redirected visual attention toward the auxiliary monitor.

The Toumai platform features a closed surgeon console equipped with an immersive 3D endoscopic system delivering 1080p full high-definition visualization with a 90-degree field of view [22]. The console incorporates a native Picture-in-Picture (PiP) functionality within its integrated image platform, allowing concurrent on-screen display of multimodal imaging sources, including intraoperative ultrasound, superimposed upon the primary endoscopic view within a single visual interface (Fig. 2C). The PiP window can be activated either from the sterile camera unit at the operative field or directly from the surgeon console. The size of the ultrasound window within the PiP display is fixed and cannot be adjusted intraoperatively.

The hinotori™ system features a closed console and utilizes an external Karl Storz camera endoscope that delivers 4K three-dimensional high-resolution video in widescreen 16:9 format [23]. Intraoperative ultrasound integration was achieved by connecting the ultrasound unit directly to the system tower, enabling activation of the console’s split view functionality and allowing dual vision of the ultrasound imaging stream alongside the endoscopic view within the surgeon console (Fig. 2D). The system offers display flexibility: a double-click on the camera foot pedal allows instant toggling to full-screen endoscopic view, restoring complete operative field visualization when ultrasound guidance is temporarily not required. Furthermore, the console supports a three-panel split view, enabling simultaneous display of the endoscopic image, the ultrasound feed, and a third external imaging source.

In all platforms, real-time B-mode imaging was successfully displayed at the console without measurable latency.

Table 2

Platform-specific modalities for intraoperative ultrasound image integration at the surgeon’s console across the four evaluated robotic systems.

Platform	Display integration	Notes
Da Vinci Xi	TilePro software	Simultaneous robotic and ultrasound view; adjustable window sizing.
Hugo™ RAS	Touch Surgery ecosystem	External display workflow using an auxiliary monitor adjacent to the console.
Toumai	Picture-in-picture	Ultrasound image overlaid on the robotic field withing a single interface.
hinotori™	Multi-input display	Dual or triple simultaneous sources; full-screen toggle when ultrasound is not required.

Instrument Selection and Probe Manipulation

All four platforms allowed stable grasping and intracorporeal manipulation of the drop-in probe using standard robotic instruments. Robotic wrist articulation enabled image acquisition at angles not achievable with conventional rigid laparoscopic probes, confirming the ergonomic advantages previously described in the literature [12]. The following observations reflect the technical recommendations of two experienced operators, a robotic surgeon and a specialist in intraoperative percutaneous, open, and laparoscopic interventional ultrasound, and are intended as practical guidance.

On the da Vinci Xi multiple graspers were evaluated for probe holding, including the Cadiere forceps, ProGrasp® forceps, fenestrated bipolar forceps, and Maryland bipolar forceps. The Cadiere forceps provided softer tissue engagement, while the ProGrasp® offered a stronger grip; the fenestrated bipolar forceps allowed immediate access to bipolar energy without instrument exchange. The Maryland bipolar forceps was identified as the preferred instrument, offering the optimal combination of grip stability and fine spatial control for probe manipulation.

Among the options evaluated on the Hugo™ RAS, the Cadiere forceps was identified as the most suitable grasper, as its straight jaw profile allows a secure grasp of the probe clip compared to angulated alternatives.

On the Toumai platform, four instruments were tested: the fenestrated Cadiere forceps, the Maryland forceps, the standard Cadiere forceps, and the fenestrated bipolar forceps. The standard Cadiere forceps was selected as the preferred instrument owing to its superior grip stability during probe manipulation. The fenestrated bipolar forceps represented a valuable alternative in operative scenarios requiring intraoperative hemostasis, as it permits immediate activation of bipolar energy without requiring instrument exchange.

On the hinotori™ system, five instruments were evaluated: the bipolar fenestrated grasper, the Versatile Grasping Forceps, the Universal Grasping Forceps, the Croce Grasping Forceps, and the Maryland forceps. The Universal Grasping Forceps is functionally analogous to the Cadiere forceps used on other platforms; the Versatile Grasping Forceps was identified as the instrument of choice, providing the greatest probe stability during manipulation. The bipolar fenestrated grasper, the Croce Grasping Forceps, and the Maryland forceps all demonstrated satisfactory performance and represent viable alternatives depending on operative requirements.

Although better grip and manipulation were observed with the preferred graspers listed above, both ultrasound probe models could be used with all available graspers tested on each platform. No relevant difference in clip grip was observed between the L43K and L51K probes.

Discussion

In this study, a standardized RIOUS workflow using two system-agnostic drop-in probes was successfully completed on four architecturally distinct multi-port robotic platforms (da Vinci Xi, Hugo RAS, Toumai, and hinotori). On every system, both probes were inserted and manipulated

intracorporeally with standard robotic instruments without probe detachment, cable entanglement, or arm interference, and real-time B-mode imaging was displayed at the console or on accessory monitors. Platform-specific differences were confined to room layout, console image-integration modality, and preferred grasper selection, while the core procedural steps (machine positioning, trocar strategy, probe insertion) remained consistent across systems. To our knowledge, this is the first multiplatform technical demonstration of a RIOUS workflow, showing that a common procedural framework is feasible and reproducible across platforms with markedly different architectures and imaging ecosystems.

As the number of commercially available robotic platforms continues to grow, the absence of a universal RIOUS workflow risks creating platform-specific silos that limit the transferability of ultrasound skills and hinder the broader adoption of intraoperative ultrasound in robotic surgery. The present protocol addresses this gap by identifying a common procedural framework, acknowledging and accommodating the technical specificities of each platform. A key enabler of this cross-platform compatibility is the system-agnostic design of the drop-in probes. The clip-based attachment mechanism and flexible cable of the probes make them compatible with any robotic grasper capable of a stable precision grip. This versatility aligns with the broader trend toward modular, interoperable surgical technologies and reduces the economic burden associated with platform-specific hardware development.

Regarding console image display, real-time ultrasound visualization was successfully achieved across all four platforms, albeit through substantially different integration modalities. Split-view configurations, as implemented on the da Vinci Xi and hinotori systems, maximize the spatial integration of the ultrasound image within the operative field by allocating a dedicated display partition alongside the endoscopic view, preserving the surgeon's simultaneous perception of both imaging domains at full console resolution. In contrast, overlay solutions, such as the Picture-in-Picture functionality of the Toumai platform, offer the advantage of maintaining a complete view of the operative field, at the cost of a reduced ultrasound window size; this trade-off may be advantageous in scenarios where continuous operative field awareness takes precedence over detailed sonographic assessment. The auxiliary monitor approach adopted for the Hugo RAS, while effective, introduces a degree of visual displacement that requires the surgeon to redirect gaze away from the primary console display, a factor with potential ergonomic implications during prolonged or technically demanding procedures. Future developments in augmented reality and intraoperative image registration are expected to further harmonize these experiences across platforms, as their convergence with robotic intraoperative ultrasound workflows represents a natural evolution toward a unified, platform-agnostic standard for real-time image-guided surgery [14].

The telesurgical dimension represents a forward-looking contribution. The concept of robotic tele-image-guided surgery, in which a remote operator manipulates a drop-in probe under image guidance while a primary surgeon operates, has been theorized but never technically demonstrated across multiple platforms [24]. The present work lays the procedural groundwork for such scenarios by confirming that drop-in probe manipulation is feasible via robotic arms and may be implemented also in remote console configurations where available. This has direct implications for the future of surgical oncology,

particularly in settings where specialized image-guided expertise is geographically concentrated, and where telementoring or tele-assistance could extend its reach to underserved institutions.

A key methodological contribution of the present study is the development of four structured, platform-specific video demonstrations documenting the complete RIOUS workflow from ultrasound machine positioning to console image integration and probe manipulation, available as Supplementary Materials. These recordings are intended to serve as practical reference tools for surgeons approaching RIOUS for the first time on any of the evaluated platforms, as well as for training programs seeking to incorporate intraoperative ultrasound into robotic surgical curricula. In this context, the integration of real-time intraoperative ultrasound assumes relevance in robotic surgery, where the absence of haptic feedback represents a well-recognized limitation of current platforms [13]. The inability to perceive tissue resistance, organ consistency, or subtle textural differences renders the surgeon exclusively dependent on visual input for intraoperative spatial orientation and tissue characterization. Real-time ultrasound imaging may directly address this sensory gap by providing an additional visual information layer that partially compensates for the loss of tactile perception, enabling tissue differentiation, vascular assessment and lesion localization that would otherwise rely on tactile cues [25]. This augmented intraoperative perception carries oncological significance in procedures where real-time imaging findings are expected to directly inform surgical decision-making. In the setting of cancer surgery, intraoperative sonographic assessment may act as a decision-making tool, influencing the extent and radicality of the planned intervention, or refining surgical strategies in 25–40% of cases [26]. The ability to evaluate lymph node morphology, echogenicity, and vascular architecture in real time allows for dynamic modulation of the lymphadenectomy extension and may in selected cases justify the suspension of primary surgical procedure in favor of reorientation toward alternative therapeutic strategies, thereby enabling timely access to appropriate oncological treatment [6].

Furthermore, RIOUS holds potential for intraoperative guidance of robotic procedures targeting metastatic disease. Early experience with robot-integrated intraoperative ultrasound in hepatic surgery confirmed the feasibility and added value of direct console-based sonographic guidance during robotic liver resection [12], while robotic-assisted ablation has demonstrated superior targeting accuracy and procedural efficacy compared to freehand techniques and a reduced learning curve for less experienced operators [27]. Although that evidence refers to non-surgical percutaneous robotic systems, it supports the broader concept that robotic assistance can enhance precision in image-guided procedures. The integration of a system-agnostic drop-in probe within a fully robotic workflow may represent a further step toward enabling intraoperative ablation guidance directly from the surgeon console, without requiring a separate interventional radiology team or a hybrid operating room setup. As robotic platforms continue to evolve in terms of dexterity and imaging integration, stereotactic and robotic interventions are expected to become an integral component of the multimodality management of malignant liver tumors, with real-time intraoperative ultrasound serving as an enabling technology for precise lesion targeting, ablation monitoring, and margin assessment [28].

While the diagnostic and therapeutic potential of IOUS/RIOUS is supported by evidence, its integration into routine practice requires acknowledgment of the barriers that currently limit widespread adoption, spanning technical, operational, educational, and economic domains [26]. Addressing these challenges demands coordinated investment in technological innovation, training standardization, and rigorous outcomes research. In this regard, a meaningful finding emerging from this study is that, once foundational competency in intraoperative ultrasound imaging has been acquired, dedicated platform-specific retraining may not be required, since the same workflow for system set-up and probe manipulation proved applicable across different robotic systems. This cross-platform reproducibility suggests that RIOUS proficiency may be transferable across platforms without the need for entirely separate learning curricula, significantly lowering the educational barrier to adoption at institutions transitioning between robotic platforms or operating in multi-platform environments. Whether sonographic interpretation skills themselves demonstrate equivalent cross-platform transferability remains to be formally established in future studies, but the present findings provide a procedural foundation for such investigation.

Given the well-documented role of video-based learning in surgical education, and the platform-specific technical nuances identified in the present study, standardized video documentation represents a reproducible and scalable medium for disseminating procedural knowledge across institutions with different robotic systems installed [29]. To our knowledge, this is the first collection of multiplatform RIOUS workflow demonstrations produced under identical experimental conditions, which further strengthens their value as comparative educational resources.

However, some limitations of this study merit acknowledgment. First, all evaluations were conducted on an abdominal phantom, which is an advantageous setting to reduce procedural variability, but it cannot fully replicate the complexity of in vivo operative conditions. The translation of the described workflow to clinical practice requires prospective validation, as tissue deformation, respiratory motion, organ displacement, and intraoperative bleeding represent variables that are not adequately reproducible in a phantom model. Second, the study was confined to multi-port robotic platforms; single-port systems were not evaluated. The inclusion of single-port architectures in future investigations would be of relevance, as these platforms offer the potential to further reduce the number of abdominal accesses required, minimizing surgical trauma and potentially expanding the applicability of RIOUS in less invasive operative configurations. Third, no telesurgical simulation was performed. Validating the described workflow in a teleoperated setting would substantially strengthen the translational value of these findings in the context of tele-image-guided surgery. Fourth, the evaluation was limited to a single ultrasound system and two drop-in probe models; the generalizability of the workflow to other commercially available drop-in transducers and ultrasound platforms remains to be confirmed. Fifth, all procedures were performed by highly trained experts, introducing a potential operator bias that may limit the applicability of these results to centers with less specialized robotic ultrasound experience; furthermore, inter-operator reproducibility was not formally evaluated, and future studies should address the consistency of workflow execution across operators of varying expertise levels. Finally, no formal

assessment of task completion time, image quality metrics, or operator workload was performed, which would provide objective benchmarks for future comparative studies.

Conclusions

The present study demonstrates that a standardized, reproducible workflow for robotic intraoperative ultrasound using system-agnostic drop-in probes is feasible across four major robotic surgical platforms. These probes are not restricted to a specific robotic system and can be employed across different platforms, allowing a common procedural framework to be applied consistently across institutions. The accompanying video demonstrations provide structured, step-by-step reference material intended to support surgeon training, facilitate platform-to-platform skill transfer, and promote the wider adoption of RIOUS in robotic surgical practice. The findings also lay the technical foundations for future integration of ultrasound-guided robotic surgery into telesurgical and tele-mentoring workflows, with potential implications for remote precision surgery.

Declarations

Authors' Contributions

Study design: MEG, CI, MP, JM. Data collection: CI, FE, DK. Data extraction: CI, FE. Drafting of the manuscript: CI, MP, MEG. Critical revision: JM, AF. All authors have read and commented on the working versions and approved the final manuscript before submission.

Disclosure

IRCAD, as an academic Institute, receives grants from several companies, including Karl Storz Endoskope, Beijing Surgerii Robotics Company Limited, EndoQuest Robotics, Harbin Sagebot Intelligent Medical Equipment Co., Ltd., Intuitive Surgical, Medcaroid, Medtronic and MicroPort. The other authors declare no competing financial interests.

Intuitive has not validated or endorsed the use of third-party ultrasound equipment with its robotic systems; and this publication should not be interpreted as instruction for use, workflow validation, intended use expansion, or formal compatibility/endorsement by Intuitive.

Mariano Eduardo Giménez serves as a consultant for FUJIFILM Healthcare Corporation and for Medtronic. All other authors have no relevant financial or non-financial interests to disclose.

Availability of Data

All data generated or analyzed in this study are included in this article and/or its figures. Further inquiries may be directed to the corresponding authors.

Institutional Review Board Statement

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Informed Consent Statement

Not applicable.

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Figures

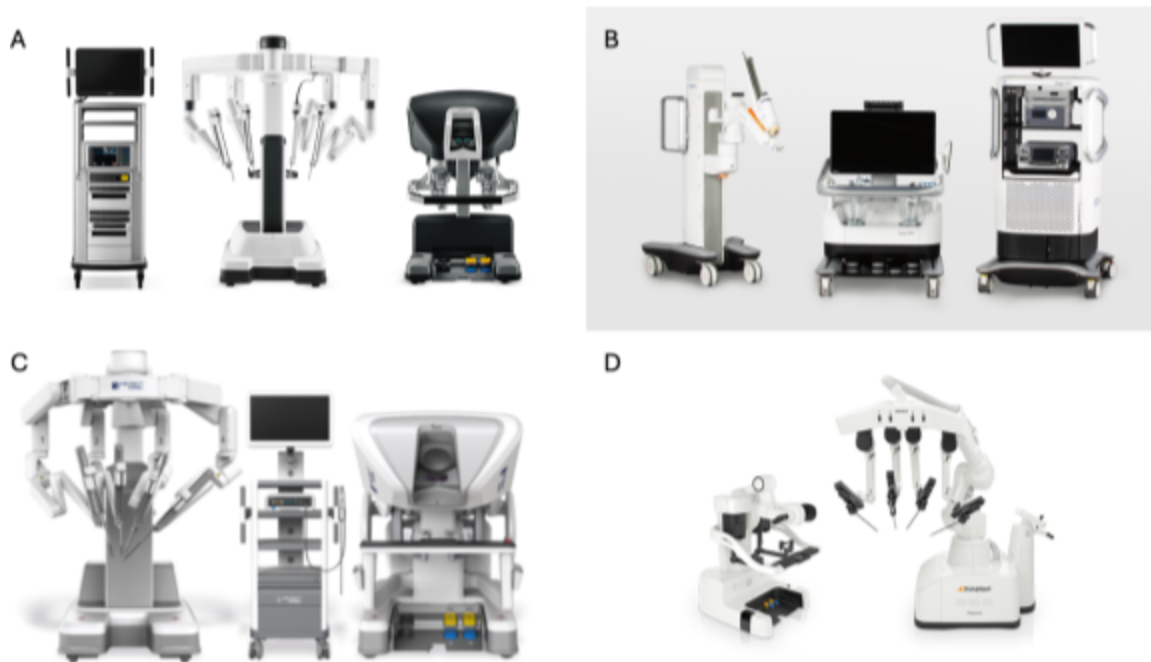


Figure 1

Multiport robotic surgical systems used.

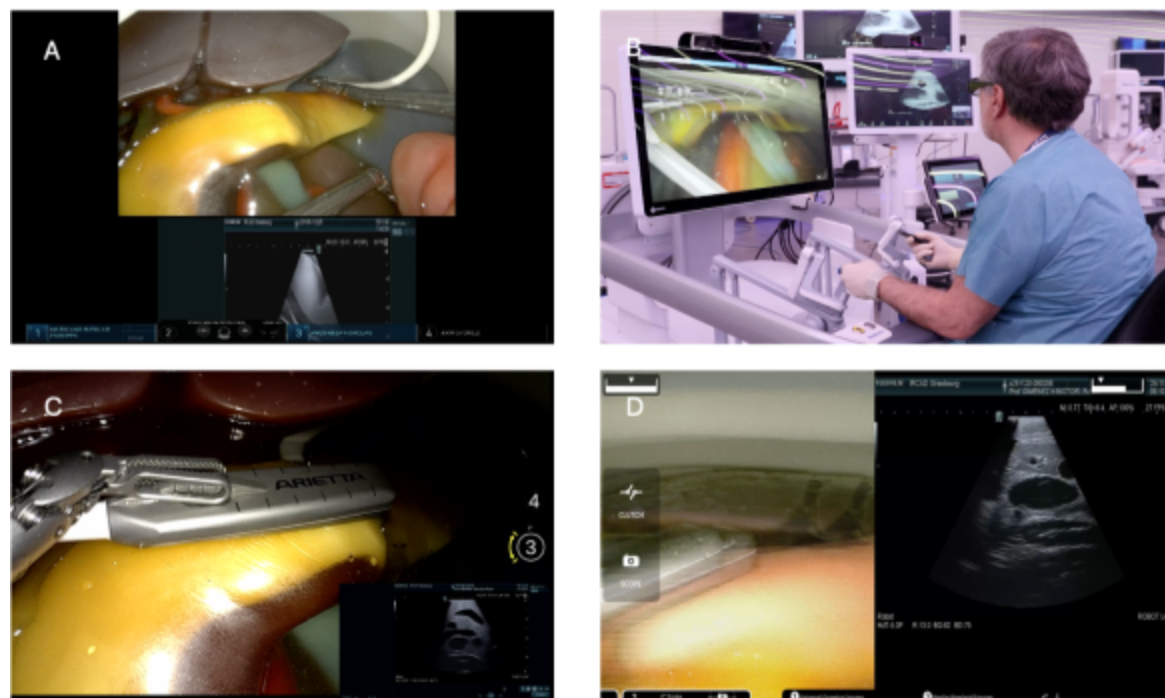


Figure 2

Outputs of platform-specific modalities for intraoperative ultrasound image integration at the surgeon's console across the four evaluated robotic systems (A, Da Vinci Xi; B, Hugo™ RAS; C, Toumai; D, hinotori™).

Supplementary Files

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