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Remote and Telerobotic Ultrasound Imaging

REVIEW

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ABSTRACT

Echocardiography and ultrasonography are mainstay imaging modalities for the diagnosis, management, and surveillance of widespread acute and chronic illnesses, including cardiovascular disease. As such, they contribute to improved outcomes. Skilled sonographers are currently required to perform complete diagnostic exams; however, a critical shortage of sonographers in isolated, rural, remote, and global locations contributes to known healthcare disparities. Telerobotic ultrasound systems, which assist sonographers in using a robotic arm to examine patients remotely, offers a potentially profound impact. While this approach represents the intersection of telehealth, robotics, and imaging, important logistics must be addressed to achieve widespread adoption. These include integration of systems and workflow, the need for robust networks, cybersecurity, haptic feedback, cost/billing, and regulatory aspects. The utility, development, technical requirements, and future applications for these technologies are described here.

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INTRODUCTION

Telerobotic ultrasound research and development has been described since the late 1990s.[1] In 2009, Boman et al. introduced the concept of CARdiological consultation at a DISTance (CARDISTA), wherein a cardiologist and a sonographer, distant from the patient, used a remote robotic arm (Medirob) and a portable ultrasound machine at the patient site.[2] The recent expansion and acceptance of telehealth for clinical appointments, continued advances in fifth generation (5G) networks for video and data transmission, and medical robotics all intersect to make the widespread clinical use of telerobotic ultrasound possible. Rural and global healthcare disparities in cardiac care, resulting from the unequal distribution of specialists and sonographers/echocardiographers, can be addressed with telerobotic ultrasound by making echocardiography widely available in most isolated areas, developing countries, and in emergencies, disasters, or combat settings.[2,3]

The European Union and the World Health Organization have identified the development of mobile health systems and services as a top priority[4] given the rapid development and widespread use of telehealth—which includes all aspects of medical care such as workflow, nursing, pharmacy, and social services. Included under this umbrella term is "telemedicine," the delivery of health care and sharing of medical knowledge that includes diagnostic tests, patient monitoring, and facilitating access to specialists. This form of medical "visit" became mainstream during the COVID-19 pandemic, when the need for isolation became paramount. The emerging next evolution of telehealth could logically include the expansion of remote diagnostic imaging such as echocardiography, ultrasound, and ultimately procedural care.

Telerobotic echocardiography/ultrasound offers a perfect first use case given the high need, low risk, and unavailability of sonographers capable of performing a complete diagnostic exam. Multiple early proof-of-principle global clinical applications illustrate the potential for the transformative convergence of robotics, telemedicine, and cardiovascular imaging.[3] Widespread adoption, which is needed to address dire healthcare disparities, is only now becoming possible as the required telecommunication and robotic technologies advance.

CARDIAC DISEASE AND ECHOCARDIOGRAPHY

Cardiovascular disease, including heart failure, remains a leading cause of mortality, necessitating timely diagnosis and management.[5] Echocardiography remains the mainstay of imaging in the diagnosis, screening, risk stratification, and monitoring of cardiovascular diseases, in accordance with established guidelines.[6,7] Routine and emergent echocardiography is used in the setting of pericardial effusion, cardiac tamponade, valvular disease, left ventricular dysfunction, ischemic heart disease, pulmonary embolism, cardiac arrest, and aortic dissection[8] to assess cardiac function, hemodynamics, valvular function, and myocardial ischemia. Numerous studies show that the use of echocardiography improves inpatient mortality rates.[9,10] Higher hospital echocardiographic volumes have been associated with reduced inpatient mortality in patients admitted with acute heart failure.[10]

While echocardiography required during most cardiovascular emergencies is time-sensitive, standard echocardiography is not readily available or is associated with significant delay in rural/remote settings[11] because trained sonographers and specialists tend to work in metropolitan and suburban settings and much less in rural, remote, and underserved settings that face healthcare disparities. In addition, echocardiography requires a high degree of skill on the part of the examiner to perform a complete comprehensive diagnostic exam, and the current demand for sonographers has outpaced the supply, straining the healthcare system.[7,12,13]

In fact, the shortage of qualified sonographers/echocardiographers in rural community hospitals is a critical, long-standing, and worsening issue with no adequate solution.[12,14] As a result, patients in these underserved areas may not get echocardiography, ultrasound, or related specialty health care. For example, a study of patients in the Veterans Administration (VA) Healthcare system reports that echocardiography utilization significantly drops at distances greater than 50 miles from the nearest VA Medical Center.[15] This workforce deficit leads to a healthcare disparity whereby patients in rural/remote areas are forced to travel long distances, endure lengthy wait times, or go without necessary care, contributing to higher hospitalization rates, more advanced diseases at the time of diagnosis, and higher mortality rates in rural populations compared to urban areas.[12]

Furthermore, skilled echocardiographers/sonographers are not available in more extreme environments such as disasters, war zones, oil drilling platforms, the tundra and arctic, nor on ambulances and during medical air transport. As the most extreme example of telerobotic ultrasound, Arbielle et al. successfully performed remote echocardiography for astronauts on the International Space Station.[16] All scans were performed with a delay of approximately 1 to 2 seconds (delay of 400 ms up and 400 ms down; ascending flow rate of 1 Mbit/s; descending flow rate of 4 Mbits/s; frame rate of 12 frames/s; loss of information 1.9% up and 0.05% down), which required the sonographer to work slowly to ensure that additional commands were not sent to the probe or echograph before seeing the effects of the previous commands. An additional uplink/downlink line allowed the sonographer and the astronaut to talk to each other while providing cabin video with a slight 1-second delay.

While not within the scope of this review, the details and logistics necessary for telerobotic echocardiography described herein could be applied to any telerobotic endovascular procedures, such as telerobotic stenting. In 2019, Patel et al. described telerobotic-assisted percutaneous coronary artery interventions (PCI) conducted over a distance of 32 km[17] using a CorPath GRX robotic system (Seimens Healthineers). In 2020, Madder et al. used wired networks and 5G wireless networks to perform successful remote transcontinental telestenting.[18] The remote use of the CorPath GRX system has been well-documented in the context of both PCI and peripheral artery disease angioplasty.[18,19]

HEALTHCARE DISPARITIES AND SONOGRAPHY

According to recent United States (US) Census Bureau reports, approximately 97% of US land area is rural. Roughly 60 million Americans, or 21% of the population, reside in rural towns.[20] Patients in rural areas tend to have more chronic health conditions and live farther from healthcare services. An analysis of healthcare access in rural America showed 31% fewer medical specialists and 23% higher annual mortality rates compared with urban areas.[21] A known paucity of specialists, including cardiologists, in rural communities leads to healthcare disparities. One 2024 study found that only 8% to 10% of all physicians choose to practice in rural settings.[22,23] A study between 2008 and 2010 demonstrated that roughly 15% of diagnostic technologists worked in rural communities.[23] Furthermore, the need for echocardiography and/or ultrasonography is increasing as the patient population ages, resulting in greater strain on the healthcare system, particularly in already underserved areas, exacerbating the sonographer maldistribution.

The shortage of sonographers is further compounded by known significant work-related injuries and occupational hazards. Sonographers must move the probe within the field of interest, provide subtle corrections to probe position and angulation, and adjust imaging parameters—all while providing significant force on the probe to maintain image quality.[24] Reports indicate that 65% to 91% of sonographers experience neck, shoulder, arm, and back pain, bursitis, muscle strain, and peripheral nerve pathology related to moving the patient as well as the ergonomics of holding the probe with the appropriate angle and pressure to obtain a diagnostic exam.[25-28] Sonographers frequently find themselves in uncomfortable positions when manipulating the probe for extended periods, ranging from 5 to 60 minutes per exam, resulting in these injuries and temporary or permanent disability, particularly in older more experienced sonographers**.** A 2002 study suggested related gross lost revenue ranging from $25,000 to $60,000 per month per sonographer due to work-related injury.[26]

In underserved, remote, and rural settings where trained echocardiographers are not available, or even during off-hour emergencies in metropolitan areas, expert acquisition is still necessary for a full echocardiography, including Doppler. One attempt to address these shortages has been point-of-care ultrasound (POCUS), wherein any health professional can use a portable ultrasound to obtain limited ultrasound images.[29] However, these POCUS exams are often found to be incomplete and of nonuniform quality, with risks of nondiagnostic and misleading imaging.[30] Furthermore, time taken for the clinician or emergency transport personnel to perform POCUS distracts from emergent clinical care, stabilization, and therapeutic management compared with dedicated and trained sonographers who are not responsible for overall patient care.

TELEROBOTIC ULTRASOUND: AN EMERGING FRONTIER

The shortage and maldistribution of qualified sonographers and echocardiographers is a critical and worsening issue with no foreseeable adequate solution.[31] Thus, the potential impact of a telerobotic ultrasound system is profound. The wide availability of information technology and wireless transmission has allowed development of electronic health to address healthcare disparities and now is being applied to telerobotic solutions.[32] In this approach, offsite skilled sonographers as well as cardiologists control a distant robotic ultrasound system to remotely move the ultrasound probe on the patient and perform the echocardiogram/ultrasound.[24]

Remotely operated robotic ultrasound has been a research interest within medical robotics and ultrasound communities since the late 1990s.[32,33] Over the last 20 years, many systems with different mechanical configurations have been proposed.[32-34] Robot-assisted teleoperated ultrasound has been demonstrated to be feasible and safe, with multiple types of ultrasound examinations having been performed in remote areas with a high success rate, nearly comparable to that of conventional manual sonography.[34] The most extreme examples are the use of telerobotic ultrasound on the International Space Station across several studies, including the European Space Agency's sponsoring of the "Advanced Robotized Tele-Echography Integrated Service Project,"[35] and in military garrisons based in Lebanon and Afghanistan[36] that led to lowering morbidity and optimizing cardiovascular health outcomes.[37]

The robots used can be divided into three categories: (1) purpose-built robots designed specifically for remote ultrasound examination; (2) adapted industrial robots (traditionally fabricated for manufacturing lines); and (3) collaborative robots (cobots), typically operating at lower speed and equipped with force and torque.[34] Remote control of a robot requires a master system of varying complexity, ranging from a joystick to a system tracking the sonographer's hand motion and transferring the data to the robot to move the attached ultrasound probe. Additionally, a haptic device can capture the operator's hand motions and provide the operator with a sense of touch as it generates forces proportional to the robot's interaction with the remote environment.[34,38]

Robotic arms such as the Kuka LBR iiwa (Kuka AG Robotics) or the UR10 robots (Universal Robots) provide full control of the position and orientation of an ultrasound probe.[34] Serial robots with 6 degrees of freedom (DOF) execute orientation motions with the 3 DOF associated with the wrist of the robot and the positioning achieved with the other 3 DOF known as base, shoulder, and elbow.[39] This allows for a range of motion that includes three translational movements (left/right, forward/backward, up/down) and three rotational movements (roll, pitch, yaw) for angling, tilting, and sweeping the ultrasound probe.

Robotic ultrasound imaging systems also can be classified into four main categories based on their degree of automation: assistive, teleoperated, semiautonomous, and autonomous.[40] At a basic level, ultrasound scanning involves localizing the region of interest, moving the ultrasound probe to the scanning starting point, and subsequent optimization by fine angling, tilting, and sweeping the probe over the patient's skin. In assistive systems, someone located with the patient, such as a medical assistant, positions a frame against the patient while a remotely located sonographer controls a robotic arm, holding the ultrasound probe within the frame (an example of this is the AdEchoTech Melody system).[41,42] Ideally, reliance on an assistant at the patient site should be minimized since working with multiple people can lead to excess operational stress and frustration for the sonographer while also making the interface more ambiguous due to accommodating for another person's actions.[43] Thus, a desirable interface should help the sonographer maintain contact and operate probe position and orientation without any external support.

Unlike assistive teleoperated systems, a semiautonomous robotic ultrasound imaging system involves task sharing between the sonographer and the robot, with potential to automate initial and fine imaging optimization. Autonomous robots are systems capable of performing ultrasound scanning and optimizing image acquisition with minimal or no human intervention, adapting actions based on sensor and imaging input.[43] An autonomous system may reduce scanning time, increase accessibility to ultrasonography, and allow the sonographer to perform other tasks in parallel. Thus, there is a spectrum of evolving technologies from teleconsultation, where a distant sonographer or specialist guides a remote operator while performing POCUS, to completely virtual-assisted sonography as seen with artificial intelligence (AI)-assisted POCUS such as Verisound AI (GE Healthcare), Lumify (Philips Ultrasound), and EchoNuos Inc., to partial telerobotic solutions such as AdEchoTech, to emerging fully telerobotic solutions such as Apricity Robotics, Dopl Technologies, Wosler Robotics, and others.

There is growing clinical experience with telerobotic ultrasound. Boman et al. conducted a clinical study comparing the standard of care to telerobotic echocardiography in rural northern Sweden, 135 miles from the nearest hospital.[44] It demonstrated a significant reduction in the time required to provide a diagnostic echocardiogram, consultation, and management, dropping from 114 days to 26 days even though the remote robotic exam was only available every 2 weeks. Furthermore, all patients in the remote telerobotic arm of the study felt comfortable with the robotic exam and were satisfied with the information provided, and 95% reported they had received faster care compared to traditional methods. They also asserted that the remote consultation was a superior strategy for expediting their medical care, based on (1) eliminating the need to travel; (2) the speed of diagnosis; and (3) the likelihood of receiving faster treatment.[44] Thus, telemedicine—the delivery of health care and sharing of medical knowledge using telecommunication systems—is expanding to include remote imaging and procedural care including echocardiography and ultrasonography.[24]

A 2023 comprehensive review reports 10 telerobotic ultrasound clinical studies totaling 800 patients at distances from 3 to 7,000 km.[32,34] Of these studies, 40% were cardiovascular, and the rest were abdominal, renal, pelvic (50%), and lung (10%).[34] Currently, only one telerobotic ultrasound system, Melody (AdEchoTech), is approved by the US Food and Drug Administration (FDA) for abdominal, pelvic, obstetric, vascular, and musculoskeletal remote ultrasound but not for echocardiography.[42] However, that system requires an assistant at the patient site holding a frame against the patient, applying force, and moving while the remote sonographer can only tilt and angle the ultrasound probe with 3 DOF.

A large number of early and pre-clinical studies describe proposed telerobotic ultrasound systems, and a few systems have been commercialized to address rural and global shortages of sonographers, such as MGIUS-R3 (MGI Tech Co, Ltd) in Asia and Melody (AdEchoTech) in Canada. Related clinical studies have demonstrated excellent utility.[32] While great promise exists for these technologies, numerous logistics need to be addressed to allow widespread adoption, including integration of systems and workflow and the need for robust networks, cybersecurity, haptic feedback, regulatory challenges, and costs.

REQUIREMENTS FOR REMOTE TELEROBOTIC IMAGING

The development of telerobotic cardiac imaging including ultrasound and echocardiography, electrophysiology, and cardiac catheterization is poised for exponential growth. To successfully use these disruptive technologies to address related healthcare disparities, all stakeholders must develop the application and required infrastructure. In addition to the paramount importance of technical requirements for safe and efficacious procedural care, mainstream widespread adoption of telerobotic procedures will require establishment of cybersecurity, liability, hospital privileging, reimbursement models, workflow, patient adoption, and compliance with the Health Insurance Portability and Accountability Act (HIPAA)—intricacies that previously have been defined for telemedicine.

Relevant workshops with all stakeholders at one rural healthcare system focused on patient site team interactions, education and training, network security, and economics integral to telerobotic endovascular procedures.[45,46] The experience with teleradiology services established a relevant workflow model that has been incorporated into clinical practice.

Clinical, technical, and workflow/process standards will have to be established for the widespread use of telerobotic imaging and procedural care. This will aid the workforce of sonographers who may perform remote sonography from a distant, centralized center using a "hub and spoke" model. Alternatively, as has been seen with other forms of diagnostic imaging and radiology, it is conceivable that the sonographer may even be at home performing the distant ultrasound. This approach would certainly address the paucity of sonographers in rural, remote, underserved, and global settings. Table 1 summarizes the recommended and required features relevant to the sonographer and the telerobotic system at the patient and operator site.

LEGAL/REGULATORY LOGISTICS

It is likely that the operator site, patient site, and company that develop the technology will have to credential the operator and patient site ancillary care. Currently, only four states mandate state licensure for sonographers: New Hampshire, New Mexico, North Dakota, and Oregon. Otherwise, sonographers will be able to perform ultrasound exams remotely to any state except those mandating additional licensure. The American Registry for Diagnostic Medical Sonography® (ARDMS®) does provide certifications such as the Registered Diagnostic Cardiac Sonographer (RDCS) certification, which may not be required but is desirable. Other remote teleoperations certifications may one day exist as systems come into use. Medical liability coverage of the operator is expected. Some liability could conceivably be required of the technology manufacturer. Logistics for third-party payors and billing also will need to be defined, perhaps requiring new Centers for Medicare and Medicaid Services (CMS) Current Procedural Terminology (CPT) codes for remote telerobotic scanning, as has occurred for telemedicine clinic visits. Currently, additional billing codes are needed when a clinic's medical appointment is conducted over the medical center's telemedicine video network. However, given that remote teleoperated ultrasound is at its infancy, no relevant CPT codes exist currently. FDA regulatory approval, likely through a 510k pathway, will be required.

NETWORK LOGISTICS

Comprehensive consensus frameworks are essential steps toward widespread adoption. Considerable technological logistics are required to connect the robotic components, related imaging, and video over a network. Telecommunication systems require high-quality resolution and low latency without packet loss that could lead to choppiness and pixilation, ideally with a resolution of 1080P at 30 frames per second; 600 Kbps at 30 frames/s has been recommended to maintain diagnostic quality images.[47] The procedural robotic commands can be conducted across low bandwidth networks, with 512 Kbps bandwidth having been stated to be acceptable. However, for related video, imaging, and audio, 5 Mbps or higher bandwidth is preferred. Transmitted data must be encrypted for privacy and comply with HIPAA regulations.[48-50] Robotic commands must be continuously checked for relevant packet loss, delay, or disorder, stopping function if it occurs.

Fifth-generation communication technology ensures real-time, high-speed, and safe transmission of information, enabling the development of remote medical robotic

	REQUIREMENTS AND RECOMMENDATIONS
Sonographer	State licensing required in New Hampshire, New Mexico, North Dakota, and Oregon
	Possible credentialing at operator site, patient site, and the company that develops the technology
Network	Cybersecurity in accordance with FDA guidance documents
	HIPAA-compliant encrypted data transmission
	Low latency (</ = 250 ms) with minimal packet loss
	Video resolution of 1080P at 30 frames per second
	Robotic commands over low bandwidth networks (~512 Kbps)
	Video, imaging, and audio over high bandwidth (~5 Mbps)
Robotic	Ideally 6 DOF motion to duplicate all sonographer hand motions
	Regulated force and speed
	Sensors in X, Y, and Z axis
Patient Site	Medical assistant (MA) present
	Effective two-way communication with sonographer
	Patient, MA, and sonographer capacity to stop and withdraw the robotic arm
Sonographer Site	Visual and haptic feedback
	Ideally 6 DOF robotic control, mirroring all manual sonographer movements
	Control of ultrasound settings and functions

Table 1 Requirements and recommendations for remote telerobotic ultrasound. FDA: Food and Drug administration; HIPAA: Health Insurance Portability and Accountability Act; DOF: degrees of freedom; MA: medical assistant

systems requiring high-speed data transfer (up to 10 Gb/s) and minimal latency.[51,52] Legeza and others reported a threshold of 400 ms for perceivable latency between two distant sites but suggested 250 ms or less and packet loss below 3%.[47] 5G "network splicing/slicing" divides the network architecture into multiple networks,[48] allowing higher data transfer speed, reliability, ultra-low latency, and enhanced security. Stable 5G networks have made robotic surgeries possible in China, Germany, Spain, and Italy.[51] Telecom companies have expanded 5G coverage in the rural areas in the US.

SONOGRAPHER/OPERATOR SIDE FEATURES

On the sonographer/operator side, the control must be familiar and functional for the user, and a user-centered design process helps to accomplish this. For example, Giuliani et al. created the "ReMeDi" telerobotic ultrasound by involving users in all stages of development to increase the utility of the system.[53] Ideally, the operator can control the robot with 6 DOF to mirror all movements made by the sonographer when performing manual ultrasound. Of further importance is control of the ultrasound parameters with remote adjustments of ultrasound settings (including gain, focal zones, depth, frequency selection, tissue harmonics, Doppler imaging, and measurements) as well as labeling and saving images and video. However, the remote control of all the ultrasound settings is rarely developed.[54]

Controls at the operator side include four types of feedback control, with visual and a combination of visual and force being the most common (including a control with haptic feedback, dummy probes with motion sensors, and 2- or 3-dimensional [3D] computer mouse devices or joysticks).[55] Haptic feedback refers to tactile sensations provided by the robotic device to the operator. Sonographers rely on haptics to know how much force is being applied and positional movement of the ultrasound scanning relative to the surface anatomy. Haptic feedback is useful for improving the safety and efficacy of a robotic system. Several studies have demonstrated utility, most often using commercial haptic interfaces,[56] although these approaches have yet to be widely incorporated into commercial telerobotic systems.

Robotic teleoperation also can be a challenge for remote experts in terms of 3D space perception. Virtual and augmented reality has the capacity to give a remote operator and the procedural team an immersive environment with improved spatial awareness and team dynamics.[57] Augmented reality (AR) and virtual reality (VR) can provide a reconstructed 3D view of the patient room and surroundings as well as surface anatomy, which, in addition to robotic sensors, may improve safety and efficiency.[58]

CYBERSECURITY

Cybersecurity measures must be substantial to assure safety and patient security.[59] Cybersecurity concerns include privacy of patient information, someone other than the intended remote sonographer taking control of the system, and disruption of network communications. Cybersecurity risks can have an immediate physical impact on patients, creating the potential for physical harm. Mobile access would entail higher risk. Robots require software updates and patches, which are points of vulnerability.

Surgical robots include hardware, firmware, and software, each with different risks and strategies to improve safety.[59] Best practices include data encryption, antivirus software, employee training, risk-based approaches to cybersecurity, and training staff on emergency maneuvers. Secure multilevel identification processes such as facial identification or dual authenticator are now commonplace. The FDA has published extensive pre-market and post-market guidance for device cybersecurity.[60,61]

FUTURE DIRECTIONS

AI is starting to be applied in ultrasound systems, largely focusing on the analysis of images already acquired by sonographers.[62] Recently, AI also has been used to assist nonexperts in acquiring echocardiograms.[63] AI has the potential to aid teleoperation through several pathways, including deep learning for image/anatomy recognition and clinical diagnosis as well as guiding probe positioning. Several commercial point-of-care ultrasound systems are beginning to integrate these basic AI algorithms.[64] An exciting next step would be the integration of deep learning to direct the robotic arm, aiding experts when remotely controlling the telerobotic procedure and eventually enabling autonomous echocardiography/ultrasound. The strategies described for telerobotic ultrasound can conceivably be applied to any robotic procedure or surgery—including cardiac catheterization/stenting, valve repair, and ablation—to provide better care for patients affected by healthcare disparities. A universal robotic language could further enable far-reaching translation.

BARRIERS TO IMPLEMENTATION

The intent is to use advanced telerobotic technologies to address healthcare disparities related to the paucity of sonographers in remote and rural communities. While these advanced technologies are developed in large academic centers, the institutional experience must be translatable to small rural centers that are most in need of these services. An understanding of the workflow and clinical needs of the remote hospital must be considered when designing systems and their related implementation. Also, the initial and related costs must be appropriate. Finally, the workflow and network provision must be coordinated for available remote sonographers and specialists who are interpreting the imaging studies.

CONCLUSION

Long-distance telerobotic echocardiography/ultrasound could significantly improve the timely diagnosis, surveillance, and management of patients with acute and chronic disease. This is particularly true in rural, remote, and underserved settings. It is probable that telerobotic systems will become increasingly established, cost-effective, and widely adopted. Industry-wide standards for telerobotic systems and communication platforms will be necessary, and universal standards may reduce the operational, legal, and logistical barriers to facilitate widespread implementation.

KEY POINTS

- Echocardiography has a substantial clinical impact but often is not readily available in rural, remote, and global settings.
- Remote telerobotic ultrasound and echocardiography can help address disparities in cardiac care related to a shortage of sonographers in these settings.
- Widespread adoption of telerobotic ultrasound requires convergence of robotics, telemedicine, and cardiovascular imaging.
- Clinical, technical, and workflow standards are essential for moving forward with implementation in underserved areas.

COMPETING INTERESTS

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