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Future of Neurology & Technology: Neuroimaging Made Accessible Using Low-Field, Portable MRI

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Abstract
In the 20th century, the advent of neuroimaging dramatically altered the field of neurological care. However, despite iterative advances since the invention of Computerized Tomography (CT) and Magnetic Resonance Imaging (MRI), little progress has been made to bring MR neuroimaging to the point-of-care. Recently, the emergence of a low-field (LF) (<1 Tesla (T)), portable MRI (pMRI) is setting the stage to revolutionize the landscape of accessible neuroimaging. Users can transport the pMRI into a variety of locations, using a standard 110-220V wall outlet. In this article, we discuss current applications for pMRI including in the acute and critical care settings, as well as the barriers to broad implementation, and future opportunities.

Background
In 1971, the development of CT transformed neuroimaging. For the first time, the brain could be visualized noninvasively[1]. MRI further revolutionized the field by coupling an external magnetic field with radiofrequency (RF) energy to provide greater soft tissue contrast and more precise anatomic visualization than CT[2,3]. However, conventional MRI (cMRI) scanners operate at a high magnetic field strength (1.5-3 T), are costly to purchase ($1M per T), and require expensive infrastructure[4]. Patients must be moved from clinical environments to controlled access remote imaging suites, often causing delays in image acquisition. This transport is associated with cardiovascular and respiratory risks, which are exacerbated by the inability to deploy interventions in transit[5, 6]. While use of portable CT (pCT) can evade these hazards, it

carries the risk of radiation[7]. Thus, the ability to obtain MR neuroimaging at the point-of-care may reshape neurological care (Figure).

For more information on pMRI background, please refer to eAppendix 1, which includes a discussion comparing pMRI versus cMRI and pCT and an explanation of pMRI specifications. eAppendix 1 also involves a clinical case highlighting pMRI's utility and a description of similar devices.

Present Deployments

Several reports have been published describing the safe deployment of pMRI in clinical settings, including in situations where COVID-19 restricted access to conventional neuroimaging due to the risk of spreading infection[8, 9]. This work demonstrates the advantages of pMRI, which are exemplified by its ability to detect a previously unknown infarction in a COVID positive patient, later confirmed by CT[9], and the opportunity to obtain serial neuroimaging of patients. Beyond the ICUs, pMRI is potentially effective in acute environments. Work done in the emergency department (ED) setting suggests its potential utility in supplementing hyperacute neurological assessments for patients experiencing stroke symptoms[10]. For example, when AIS is suspected but CT has not revealed infarction, pMRI may potentially aid in identification of acute infarction and guide subsequent intervention. Portable MRI also eliminates the need for patient transfer to CT scanner and onto scanner table as patients stay on their stretcher for the duration of the scan. This may assist with the busy environment of the ED. Furthermore, work in the operating room (OR) setting has illustrated the viability of pMRI for tracking post-surgical including confirming correct placement of ventriculoperitoneal (VP) shunts[11].

Additionally, recent studies have established the ability of pMRI to detect critical neuropathologies including intracerebral hemorrhage (ICH)[12], midline shift (MLS)[13], acute ischemic stroke (AIS)[14], subarachnoid hemorrhage, brain tumors, and traumatic brain injury[11]. Prior work has demonstrated a sensitivity and specificity of 80.4% and 96.6% for ICH and 93% and 96% for MLS when compared to standard-of-care imaging. Infarcts were detected in 90% of known cases of AIS evaluated in Yuen et al[14]. Moreover, pMRI can be utilized as a prognostic tool as ICH volumes, ischemic infarct volumes, and MLS identified on pMRI have been shown to correlate with patient outcome[12-14]. Outside of pathology evaluation, there is preliminary evidence for this technology's utility in the pediatric population, which may hold promise to better understand brain development[15].

Barriers to use

While low magnetic field strength increases neuroimaging access, it necessitates trade-offs in image resolution and acquisition time. LF MR image quality is lower than that of high-field (HF) MRI due to decreased resolution and signal-to-noise ratio (SNR). Leveraging currently evolving advanced machine learning (ML) tools may help compensate for this in the future. In addition to ML built into current software, other ML tools are being developed. Automated Transform by Manifold Approximation (AUTOMAP) is an image reconstruction tools that boosts SNR by treating reconstruction as a supervised learning task. As opposed to the standard Inverse Fast

Fourier Transform method of transforming raw k-space data, AUTOMAP uses the forward encoding model to build images with less noise and clearer brain structures[e1].

Another set of methods of image reconstruction involves Super Resolution (SR) algorithms, which take advantage of deep convolutional neural networks trained with high-resolution images and low-resolution counterparts. One common challenge of these SR methods is the inability to accurately align HF with LF images. Another challenge is the inaccurate simulation of LF images using downsampled HF images. A newer tool, *SynthSR*, can be used to overcome these obstacles, producing higher resolution images from which reliable volume estimates can be made. Although LF MRI may not be able to depict image subtleties found at a HF level, ML tools available and in development allow for higher resolution and SNR to be achieved from noisy LF images[e2].

Other limitations of pMRI are based in its physical properties. While the open geometry of the pMRI device is less confined than a cMRI bore, its small head coil, and proximity to the magnets poses issues for some patients with claustrophobia. In addition to claustrophobia, the coil may also not accommodate patients with head circumferences exceeding the dimensions of the coil (26 centimeters (cm) wide and 20 cm high[6]), posing an obstacle for patients with larger heads, including children with hydrocephalus and associated macrocrania. Additionally, a body weight of over 200 kilograms may not be able to be positioned inside the device. Some non-portable LF MRI systems have been able to accommodate these shortcomings; for example, Synaptive's low-field MRI has an adjustable head coil with a patient weight limit of approximately 250 kg[e3]. Additionally, pMRI's current average scan time approximately ranges between 12 to 40 minutes, depending on sequences selected, which may be a limitation for patients who are claustrophobic or unstable for the timespan of the scan. Sequence development and optimization is underway to shorten the scan time.

Future Opportunities

As pMRI develops alongside the current generation of medical trainees, concerted efforts should be made to familiarize trainees with this new technology. Future use of pMRI should capitalize on its accessibility and affordability to bring MRI technology outside of traditional settings. With no need for a shielded room and no risk of radiation exposure, neuroimaging may even be brought into communities, increasing access with an emphasis on at-risk and disadvantaged populations. For example, pMRI may also benefit low- and middle-income communities and countries where cMRIs are relatively inaccessible. Increasing neuroimaging in these areas will also cultivate opportunities for understanding brain development and neuropathology in varied settings[15]. Portable MRI is currently commercially available in countries including the United States, Australia, and Pakistan and has been deployed in other areas including Germany and Malawi[e4]. One group has successfully implemented pMRI in a low-resource setting: Queen Elizabeth Central Hospital in Malawi which aided in clinical guidance when CT was not available, expediting treatment management[e5].

Other resource-limited or time-sensitive contexts that may benefit from pMRI include sporting arenas, outpatient clinics, combat zones, and other settings where brain injury incidence is high and answering time-sensitive questions is imperative. Also, through exploration in testing usage of low-field strength MR for patients with programmable implants, pMRI can potentially expand the eligibility of patients who can receive MRI scans.

Portable MRI may one day play a vital role in acute neurological settings, where timely neuroimaging is vital to coordinating rapid intervention. Mobile stroke units (MSUs) equipped with CT scanners allow for the ultra-rapid administration of intravenous tissue plasminogen activator (tPA) in 72 minutes compared to standard of care of 108 minutes[e6]. Equipping MSUs with pMRI in the place of CT could offer further benefits. Due to the use of DWI/T2-FLAIR mismatch as a marker of stroke onset, direct-to-MRI stroke care has shown to be useful in determining reperfusion therapies for strokes of unknown onset[e7]. Based on its ICH specificity, pMRI could potentially serve as a tool in an MSU for reperfusion therapy selection[12]. The impact and application of pMRI will be further increased once contrast agents that can operate at low field have been developed.

In addition to envisioning settings in which pMRI may be useful, we also anticipate that the research community will start developing ML methods for automated, reproducible analysis of low-field scans, including segmentation of regions of interest for volumetric studies, registration of scans for longitudinal analysis, and segmentation of lesions for their characterization. Moreover, we foresee the development of ML domain adaptation techniques that will enable the application of methods developed for high-field images to low-field scans.

Conclusion

Utilizing LF magnetic strength, pMRI continues to enhance the field of neuroimaging by increasing accessibility. It circumvents the possible hazards of transporting patients by bringing imaging to the point-of-care for critically ill patients. With the ability to identify various neuropathologies, pMRI can aid clinicians by supplementing conventional neuroimaging and by providing the benefits of rapid neuroimaging in resource-limited areas or time-sensitive circumstances where its value can be most impactful.

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Access eReferences here: LINK

Figure: (A) Portable MRI in an Emergency Department Patient Room and (B) Representative Portable MR Images

A. A patient scanned in low-field, portable MRI in their emergency department room with emergency department equipment operational during scanning. B. Paired images for comparison of high-field, conventional MRI and low-field, portable MRI in a patient with a right cerebellar hemorrhage with extension into the fourth ventricle.