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The Rise and Efficiency of Low Field Portable MRI Scanners

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Abstract

Since the discovery of magnetic resonance imaging (MRI) as an imaging modality, it has evolved immensely and is still doing so. Most imaging modalities have made bedside or emergency imaging possible due to their portability. This aspect is yet to be fully evaluated and established in the case of MRI as its high-field strength requires specialized infrastructure and its time-consuming nature makes its portability questionable. The goal of this review is to access the efficiency and feasibility of low-field portable MRI (pMRI) systems in a wide array of health care applications. Articles from indexed journals, on PubMed, Springer, Elsevier, etc. databases, relevant to this study were searched and reviewed. This review provides an atypical design that could be used in making a pMRI unit that could find its potential in diagnosing a wide variety of pathologies with an added advantage of imaging critical patients in the intensive care unit or patients in isolation due to its portability, imaging patients with implants or prosthesis effectively due to its low field, pediatric imaging due to its high speed, for guided interventions, imaging obese and claustrophobic patients due to its open nature, in dental imaging, extremity scanning, etc. With its vast spectrum of applications in the health care system, the future of low-field pMRI units seems to be bright.

Keywords
- bedside imaging
- extremity MR imaging
- low-field MRI
- magnetic resonance imaging
- portable MRI

Introduction

Magnetic resonance imaging (MRI) is a widely accepted noninvasive imaging modality for imaging internal structures with great precision, intricacy, and quality.[1] It uses a large superconducting bore magnet, radiofrequency (RF) pulses, a liquid cryogen cooling system, and a set of coils along with other acquisition and processing software and hardware made to work in synchrony for the production of images for diagnosis.[2] The magnetic field strength is measured in either gauss (G) or tesla (T), where 1 T = 10,000 G. But in the case of MRI magnetic field strength, tesla is more appropriate and acceptable. Based on this magnetic field strength the scanners can be classified as low (< 0.5 T), medium (0.5–1.0 T), and high (> 1.0 T).[3] Exploiting the differences in magnetic field strengths and other related factors that form an image, MRI, as a modality has ventured into various subtypes and fields of advancement that are enabling diagnosis at early stages on a rapid and large scale for a massive variety of disorders and illnesses.[1] Right from the basic anatomical MRI based on T1 and T2 contrast differences in tissues that portrays excellent morphological details to the ultrafast imaging that provides functional details—fMRI. Similar examples would be diffusion tensor imaging, arterial spin labeling, ultrahigh field neuromelanin-sensitive MRI, and quantitative susceptibility mapping that operates on the magnetic susceptibility to produce phase contrast.[4] As we have been witnessing, MRI has come a long

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way in improvement and advancement since the early 1980s when it was established. Yet, like several other man-made inventions MRI too has its downside, the acquisition of MRI data are an inherently slow process due to the high sampling requirements and thus cannot be used as an emergency modality where quick diagnosis and immediate action are the key. Also, the long data acquisition time leads to low patient throughput, discomfort, motion artifacts, and costly examinations. These drawbacks have motivated the development of methods for faster MRI.[5] The large and specific infrastructural demand for the installation of the MRI system makes it difficult for bedside diagnosis in cases of immobile or critically ill patients. The development of a portable, low-cost MRI device for body imaging could expand access and feasibility of MRI and enable point-of-care (POC) diagnostics thus enhancing its use in the medical arena.[6]

Importance in the Portability of an Imaging Modality

Mobile or portable radiography refers to the one that is performed outside the comforts of the radiology department with an instrument that can be moved and maneuvered single-handedly. This is performed in times when patient transfer could lead to worse complications and danger to patients' health. It could be in places within the hospital like the intensive care units (ICUs), coronary care units, cardiac surgery units, neonatal or pediatric care units, accident and emergency department resuscitation units (casualty), and postanesthesia care units (theater recovery rooms), etc. It could also be in places outside the hospital like the nursing care center, military field hospitals, sports arena, hospice, etc.[7] Quick diagnosis becomes highly essential in cases where immediate action and treatment is required to save lives, and this has been made easy and possible due to the portability of radiological imaging modalities.

Portable Ultrasonography

Ultrasound (USG) machines have truly come a long way and are available in various sizes and specifications and accessible to patients at their bedside. These can be dragged single-handedly by their wheels or are even available as completely compact hand-held devices. An added advantage of it is the use of sound waves and not ionizing radiations apart from its efficiency and cost-effectiveness.[8] MRI can definitely take a lesson or two from the efficiency of the portable USG machines especially in terms of compactness, cost, and accessibility.

Portable X-Ray

Portable or mobile X-ray units are in extensive use for various reasons especially for chest radiographs or postsurgical examinations.[9] Yet, its source of ionizing radiations that could have harmful effects on the populations makes it questionable to use thus making it necessary for ionizing radiation-free diagnostic equipment such as a portable MRI (pMRI) unit.

Portable Computed Tomography Scanners

This equipment can be operated at the normal power supply of a hospital ward or room and does not require a specialized high-power supply. It makes it possible to scan anatomy "stat" in cases like stroke, trauma, head injury, hemorrhage, etc.[10] The disadvantage being the radiation dose to staff and patients in a ward or surrounding the portable scanner due to the utilization of high-energy ionizing radiation while also lacking the soft tissue contrast imaging efficiency when compared with MRI.[8] These properties of low demand of power supply, immediate diagnosis with high contrast resolution in critical illnesses, and without conferring the ill-effects of radiation dose to the people around seen in pMRI systems are a plus point.

Portable MRI Systems

Even after 45 years of discovering the MRI scanner, portable systems were not developed.[8] Mostly owing to its complexity, bulk, and high-end equipment requirement. Though MRI had excellent image quality and also uses nonionizing radiation, it did take time and effort in innovating a low-field, low-cost pMRI scanner. This is made possible by using a permanent magnet, which increases the feasibility and accessibility to a wide range of the population. The low field also diminishes the fringe-field shielding challenges.[11]

Equipment Construction and Working Principle

The Bore-Magnet

Low-field pMRI systems that operate at a magnetic field strength of 0.25 and 0.5 T, are made either using a permanent magnet based on rare earth material, neodymium-iron-boron (NdFeB) covered by fiberglass,[12] or one that combines a permanent magnet with an additional electromagnet.[13] The cylindrical permanent magnet discs further consist of many varied sized smaller pieces of magnetized materials each of approximately $1 \times 1 \times 14$" dimensions that store energy. The geometries of which are optimized to produce the strongest and most homogeneous field that is maintained without any power supply and has a cryogen-free operation.[8,13] The entire assembly sits on a set of aluminum rollers that are covered with high-friction urethane.[14]

The Gradient (Image Encoding) System

The gradient system or image encoding usually requires a 3-axis gradient system, having one on each axis. The pMRI scanner avoids this by building in a "permanent" gradient into the magnet and utilizing that field for either readout or slice selection.[8] Another advanced way of image encoding described elegantly by Cooley et al,[14] is based on rotating spatial encoding magnetic fields where the bore magnet and linear gradient coils are replaced with a rotating permanent magnet featuring an inhomogeneous field pattern that is exploited for spatial encoding. This technique not only helps in reducing the extra magnetic material required thus aiding in the lightweight machinery but it also replaces the function of heavy switchable gradient coils with significant power requirements thus reducing the noise and cost. This synchronized magnet rotation of one degree at a rate of 10°/s is incorporated into the pulse sequence, and so is controlled with precision by the MRI console.[14]

RF Subsystem

The RF pulse transmits and receives demand of portable and low-cost MRI identical to the conventional systems. Using a low-field system increases the power efficiency of excitation, and therefore only around 5 kW (kilowatt) of RF receiver coil strength is needed for a head scanner and even lesser for an extremity scanner but higher strength coils would be required for a multipurpose whole-body pMRI scanner.[8] A fully integrated dual-channel complementary metal–oxide–semiconductor receiver chip fixed on the surface coils described by Sporrer[15] holds a brighter promise in the further advancement of the portable scanner. The integrated circuit minimizes the size of the receiver modules by completely removing all shielded RF cables. Also, the immediate digital signal conversion paves way for efficient data transmission leading to greater signal strength.

Portable MRI Scanner: A Boon

Using low-field strength accentuates patient safety and comfort, in terms of reduced projectile risks, implant compliance, and the possibility to image closer to implants due to smaller magnetic susceptibility artifacts, reduced specific absorption rate (SAR) limitations, and reduced acoustic noise because of lowered forces on the gradient coil windings, it also aids in easy extremity positioning due to its open structure. These systems alleviate footprint, which could take MRI to the POC. It is known to have reduced siting requirements in terms of space (just $\sim$9 m^2), weight ($>$ 1.5 tons) shielding, power, and cooling.[16,17] These are also much more sustainable, wherein relatively inexpensive repair and replacement of hardware modules is required in comparison to a superconducting magnet-based system.[13] Cardiac implantable electronic devices (CIEDs), like pacemakers, and implantable cardioverter-defibrillator are often contraindicated in MRI thus prohibiting imaging of patients with these implants thereby hampering their diagnosis.[18] However, owing to the low-field strengths of the portable scanners these patients with CIEDs can be imaged appropriately. The open nature of these scanners also enables the imaging of claustrophobic patients who would otherwise dread staying still in the deep gantry bore thus hampering diagnosis and treatment; also, oversized patients can now be more comfortable during imaging.[3]

Specific Clinical Applications

Neurological Diagnosis

Hydrocephalus: Low-field MRI could have an important diagnostic value in the diagnosis of hydrocephalus which is characterized by an excessive volume of cerebrospinal fluid (CSF) in the ventricles of the brain which in turn leads to increased intracranial pressure.[13] A study by Krishnan et al[19] elaborates on the MRI sequences for pediatric and fetal hydrocephalus, to be able to investigate all possible etiopathogenesis through the CSF pathway and assess the efficacy of treatment in a noninvasive standardized manner.

Intracranial hemorrhage (ICH): Patients that present with brain injuries or are suspected of stroke are treated immediately using thrombolytics, but these patients have to first be imaged proficiently to rule out any hemorrhage prior to the treatment.[20] Computed tomography (CT) scan has been used as of now, but owing to the higher sensitivity of MRI in characterizing the ICH thus aiding in better clinical management and prognosis, and also due to the negative effects of ionizing radiation used in CT, the pMRI holds better promise, which has been proven in a recent study by Mazurek et al,[21] where they obtained neuroimaging results that enabled easy bedside detection and characterization of ICH at par with conventional techniques (CT or 1.5–3 T MRI) in reduced time.

Ischemic stroke (IS): Stroke is the leading cause of death, among which IS is the most common finding, requiring stat treatment.[22] A pMRI that operates at very low magnetic field strength (0.064 T) used at the bedside of critically ill patients in the ICU has a novel neuroimaging solution in the subacute phase, that can acquire T1-weighted (T1W), T2W, fluid-attenuated inversion recovery (FLAIR), and diffusion-weighted imaging (DWI) sequences accurately and safely without having to transfer the patient, thus saving time in the diagnosis and hence treatment and also avoiding the further risk of complications in the patient.[23]

Intracranial midline shift: The low-field pMRI images acquired for bedside assessment of midline shift in patients with IS and ICH as well as cerebral mass effect prove to be consistent with the measurements obtained on conventional MRI and CT studies in a clinical trial conducted by Sheth et al.[24]

Pediatric or Neonatal Imaging

Using low-field pMRI scanners in pediatrics for the diagnosis of various pathologies is highly advantageous due to the vastly reduced acoustic noise, the open nature that allows direct parental participation, and the much lower SAR.[13] A study by Deoni et al[25] demonstrated the ability to acquire structural neuroimaging data in infants, children, and young adolescents. It has been proven that volumetric measurements and developmental patterns derived from higher field strength (3 T) systems are replicable using low-field portable scanners.

Isolation Patients Imaging

In cases where the disease is contagious and the patients are kept in isolation, for example, during the pandemic of coronavirus disease 2019 (COVID-19), where the transfer of the patient for imaging purposes is not safe, pMRI usage has been approved by the Food and Drug Administration.[26] Patients that suffer from any acute neuroinjury, can be successfully imaged. The low field nature also makes it possible to perform the scan without moving the ferromagnetic materials from the room including the vital signs monitor, compressed oxygen tanks, etc., thus avoiding patient discomfort.[27]

Dental Imaging

"DentMRI - Gen I" a prototype low-field scanner built to produce high-quality combined images of soft and hard biological tissues—such as teeth at approximately equal to 260 mT using two pulse sequences: Pointwise Encoding Time Reduction with Radial Acquisition (PETRA) and Double Radial Non-Stop Spin Echo (DRaNSSE) and reconstructed using both algebraic reconstruction techniques and traditional Fourier transformation, has been well penned down by Algarín et al,[28] in their recent study in 2020. The magnetic susceptibility effects, which lead to artifacts in the presence of metallic fillings or implants, are greatly reduced due to the low field scans. Though not fully portable, it holds promise for a bright future in portable dental scanning.

Extremity Imaging

The previously described Halbach design of a 50-mT pMRI scanner has been tested on both phantoms and in vivo scans of the knee of a healthy volunteer. Images were acquired at a spatial resolution of approximately $3 \times 2 \times 2$ mm and an signal-to-noise ratio (SNR) of approximately 20:1 within 12 minutes to show the applicability of the system to extremity imaging. The system has a high degree of portability with a magnet weight of approximately just 75 kg. The study proved that this design can be expanded in the future for use in the breast or spinal imaging as well.[29] Another study by Nakagomi et al[30] portrays the development of a small ($\sim$80 kg) car-mounted MRI system for human elbows using a 0.2-T permanent magnet. It has enabled easy positioning due to its open system and has been shown to render clinically relevant images, thus making it easily deployable for extremity imaging in remote areas, sports arenas, or emergency departments at ease. In yet another study, an MRI of the shoulder was performed on a 0.2-T extremity scanner utilizing a dedicated shoulder coil which proved to be an accurate predictor of rotator cuff tears, full or partial thickness tears with a sensitivity higher than 85% in each case which is more than sufficient to aid in clinical management.[31] Finally, all doubts about extremity scanners came to rest after the thorough evaluation done by Guallart-Naval et al,[16] where they tested a 70-mT extremity MRI scanner mounted on a wheeled structure. This unit weighed about approximately equal to 250 kg and could be used in various environments such as hospitals, at a house, outdoors, etc., and provided good image quality with valuable anatomical information in clinically acceptable times.

Chest Imaging

Recently, when everyone was hit hard by the devastating pandemic of COVID-19, longitudinal imaging series was warranted for a better understanding of underlying pathomechanisms of pulmonary damage, for which CT is of limited usability due to repeated exposure to X-rays. Also, higher field strength systems are prone to susceptibility effects due to direct tissue-air interface in lung imaging.[32] Hence, low-field MRI was used and it enabled a precise visualization of persistent pulmonary changes including ground-glass opacities, which were consistent with CT performed on the same day. Another study combined the high-performance hardware and software of a high-field strength MRI at a lower-field strength (0.55 T) in a COVID-19 patient that produced images with quality comparable to CT, showing potential of low-field systems that offer promise to reduce distortion for lung MRI.[33] Functional alterations associated with persistent symptoms after COVID-19 have also been successfully detected.[34] Thus, proving the potential of low-field systems for repetitive lung examinations in monitoring the reconvalescence after pulmonary infections and pneumonia.[35]

Vascular or Contrast-Enhanced Studies

It was highly doubtful whether more sophisticated magnetic resonance angiography (MRA) or contrast studies could be performed in low-field MRI scanners; however, this doubt was clarified by Masumoto et al[36] in their study in Japan, where they successfully developed an intra-arterial contrast-enhanced two-dimensional magnetic resonance dynamic subtraction angiography sequence using Magnevist (gadopentetate dimeglumine) on a 0.3-T low-field MRI scanner, thus showing the potential of these scanners in the visualization of vascular anatomy and hemodynamics. Also using these next-gen advanced 0.55-T low-field systems, it is possible to obtain time-of-flight MRA depicting vessels with comparable image quality to 1.5 T scanners.[37] Few other studies have been able to show pleasing evidences with respect to contrast-based studies.[38,39]

Interventional Procedures

The open structure of low-field scanners aids to guide interventions while the subject is within the scanner.[13] Also, the possibility of obtaining quality dynamic contrast images with high temporal resolution portrays well the potential of these scanners as a monitoring tool during MR-guided endovascular procedures.[36] MR-guided cryotherapy for malignant liver tumors performed using a horizontal-magnetic open system in a study by Dohi et al[40] and cardiac catheterization performed successfully in 7 patients with no heating caused by the guidewire or other adverse effects[41] proves the feasibility and accuracy of low-field open scanners in performing such sophisticated interventions in patients safely after incorporating some high-performance hardware or software used in higher field strength systems. Thus, curbing the disadvantage of high radiation doses to the patients while using other radiographic modalities like fluoroscopy, C-arm equipment, etc.[41]

Discussion

This review significantly proves great potential in revolutionizing bedside imaging with the advancement of an all-around, low-field pMRI scanner. For even smaller sizes and lighter weights dedicated brain or extremity scanners can be used. The portable 80 mT scanner specifically for brain imaging described by Cooley et al[6] is extremely lightweight, weighing only approximately 100 to 125 kg that works on a standard wall outlet power supply with no additional cooling required with an easy mounting facility for a quick commute. The drawback noticed was due to the usage of two permanent readout gradients instead of the rotating permanent magnet system which led to a nonlinear mapping of voxels in the image that manifest as geometric distortion.[6]

Diagnostic-grade T1W, T2W, T2 FLAIR, and DWI sequences were obtained in a time of less than 35 minutes using the currently available portable brain-dedicated MRI scanner at the Yale New Haven Hospital, Connecticut, United States, in a study by Sheth et al.[27] In this study all POC MRI findings synced with conventional radiology reports. Various diagnoses were correctly made in patients suffering from common neuroinjuries like ICH, diffuse cerebral edema, cerebral infarction, and small and large ISs, thus proving the effectiveness of portable systems in emergency and bedside neuroimaging. Drawbacks related to the decreased SNR that hamper overall image quality are expected due to the lower field strengths; however, these could be overcome by improvement in the other technical aspects, like modified pulse sequences, coils, or exploiting some deep learning techniques.[17] Apart from SNR, image distortion caused by the increased level of inhomogeneities in the main magnetic field especially while using gradient sequences, is an area where more research regarding better processing techniques to improve image quality is essential.[42]

While we talk about low-field scanners, Sarracanie et al[43] demonstrated short acquisition times with high SNR per unit time using the ultra-low field (6.5 mT) MRI, dating back to 2015. This was accomplished using the sparse sampling strategies (50% of k-space is sampled) and fully refocused three-dimensional (3D) balanced steady-state free precession sequences in an optimized electromagnet "20 cm field of view" mobile brain scanner with neither prepolarization nor cryogenics. The unique mechanism in this scanner was the use of a 30-turn 3D Archimedean spiral wire placement in lieu of conventional coils, thus ensuring that the magnetic field B_1 produced by the spiral pattern is orthogonal to the main magnetic field B_0. The hemispheric spiral design results in a very homogeneous magnetic field making it suitable for both receiving and transmitting RF pulses and thus obtaining good quality images required for basic neurological diagnosis. Thereby laying the basis of the foundation for the development of portable scanners using ultra-low field strength machinery which could lead to a further reduction in cost and acquisition time.[43] Since the last few years extensive fieldwork has been going on concerning the working, construction, and implementation of low-field, pMRI scanners; however, currently, the only available portable low-field MRI scanner is Hyperfine Swoop (►**Fig. 1**) in Connecticut, United States.[44] These scanners are slowly changing the age-old perception that lower field strengths caused deterioration of the image quality and are proving to hold great promise for the future.[17] Also, with the advent of artificial intelligence and remarkable developments in deep learning techniques, noise due to low static field strengths can be removed more effectively than before thus increasing the efficiency and potential of these low-field scanners.[37]

Fig. 1 Hyperfine Swoop portable low-field magnetic resonance imaging (MRI) system.

Conclusion

Back in the 1980s, the introduction of MRI scanners was using low-field strengths; however, due to a lack of image quality and other disadvantages higher strength scanners came into being displaying greater image quality and sophisticated added specifications.[37] With higher fields there came a need for higher shielding and more complex infrastructure and limitations that lacked portability. Hence, the renaissance of low-field scanners, which have overcome the past inadequacies using modern, improved technological advances, is surely a boon to the health care system. It can aid in bedside, outdoor, low-resource, or remote area imaging for cost-effective, quick, and efficient diagnosis. This would in turn lead to better clinical management and thus decreased mortality rates and a better life expectancy.

Authors' Contributions

Guarantor of integrity of the entire study was done by Jaseemudheen. Study concepts and Design were performed by both Tancia Pires and Jaseemudheen. Literature research and manuscript preparation were done by Tancia Pires. Manuscript editing and critical revision were done by Jaseemudheen. Both authors read and approved the final manuscript.

Conflict of Interest

None declared.

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