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Poster session

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Design and Function of MRI Scanners

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1.0 Introduction

A magnetic resonance imaging machine is a diagnostic technology developed for practice in the biomedical field. Clinicians that need to see inside the body of a patient to understand their physiological processes and anatomical structures in order to make a medical diagnosis need an instrument that can do so without harming the patient. MRI is a non-invasive method of scanning the inside of the body and sending high quality images of organs and tissues to a screen so the clinicians can make a diagnosis [1]. The design of the MRI uses a sensor array, large electromagnets and other ferromagnetic material components that make the scanning process possible, the result of which appears as a series of images of the body tissues on a monitor. The focus of this paper is to explain and describe the components and process in the designing of an MRI machine and concerns expressed over certain aspects of its design.

2.0 Major Components

2.1 External Magnet

The external magnet is the largest and outermost component within the shell-like housing of the MRI machine and can be one of three varieties: resistive, superconducting, or permanent. The material of any one of the magnets must be a conducting material that can be made into coils and run through with an electric current or magnetized produce the uniform, static magnetic field required of the scanner for the imaging process.

2.1.1 Resistive Magnets

In using resistive magnets to generate a magnetic field, the design calls for a set of four to be placed perpendicular to each other in the machine. Resistive magnets use bands of conducting material such as copper or aluminum wound in a cylindrical shape, a solenoid. Electricity is conducted around the material in a loop. As a result of the large amount of resistance to the current caused by the loop, heat is generated and must be removed from the system with a chilled water cooling system. Therefore, high levels and a stable source of electricity are required to sustain a large, constant electrical current to produce the magnetic field [2]. Machines using resistive magnets are not as power-efficient in producing the field as those implementing the design of permanent or superconductive magnets and are limited to a low strength magnetic field.

2.1.2 Permanent Magnets

Permanent, or fixed, magnets are constructed of a heavy and large amount ferromagnetic material, usually iron, that has been permanently magnetized and does not run on electricity, and produces a low strength field. The design structure of the magnet is in the shape of a square C, creating an open bore MRI. The ends of the C create the magnetic field and in between which the patient's body is placed for scanning. Although an advantage in using this magnet is that it does not require a cooling system to transfer heat out, it is susceptible to minor temperature changes in the room that the machine is in, which can result in a disruption of the homogeneous, or uniform, state of the magnet field [2].

2.1.3 Superconducting Magnets

MR machines commonly use superconducting magnets; there is very little resistance to the electrical current due to the material of the coils used to build the magnet and the conditions under which it is housed. A large, continuous magnetic field is easily produced. The magnet is a coil of superconducting wires made out of an alloy, a niobium-titanium alloy or niobium-tin alloy in a solenoid shape surrounded by an insulating copper matrix. In its entirety it is ring shaped along the length of the cylinder of the closed bore machine structure. The coil, wire alloy and copper matrix, is kept cool inside a volume of coolant, usually 1,700 liters of liquid helium in a dewar at almost absolute zero temperatures. At this temperature the wire becomes a superconductor, able to have as little resistance as possible to the current and the magnet only requires low levels of electricity to sustain the field [2, 3].

2.2 Gradient Coils

Gradient coils are made of narrow pieces of copper wound into long, thick wires made to conduct large amounts of electricity. These wires are looped around a center piece and all together form the three sets of coils which curve to the shape of the closed bore tube housing. The coils are situated specifically for each spatial plane, the x, y, and z planes, in order to work in a three-dimensional area around the subject. The x coils are located on the both sides, the y coils on the top and bottom, and the z coils are at each end to work the length of the cylinder, from the head to the foot of the patient. X and Y coils are saddle coils and Z coils are Helmholtz coils [2]. The positioning of the coils around the cylindrical bore of the machine is shown in Fig. 1.

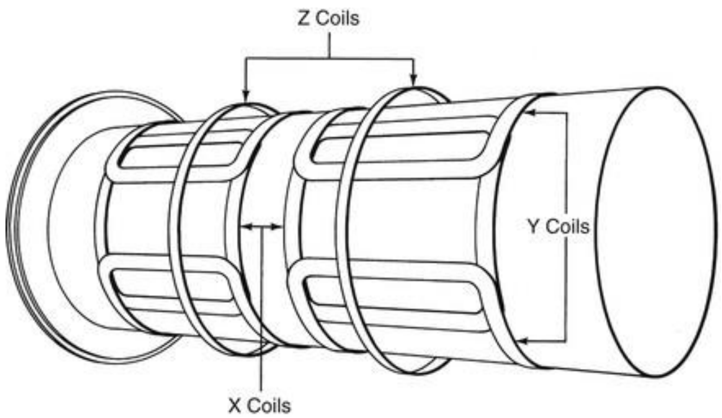

Fig. 1 Gradient Coil Configuration [4]

The coils send pulses between one another in an area; they cause the original magnetic field produced by the external magnet to vary in gradients where it is stronger in some locations. This localization of the field creates an image slice where desired of the patient. Gradient coils are located on the inside of the external magnet.

2.3 RF Coils

Radiofrequency coils are arrays of conductive wire and can be transmit only, receive only, or both a transmitter and receiver. The function of a radiofrequency transceiver is to send and receive signals to and from a small area of the patient's body. The component is positioned close to the patient around the head, body, or on a small section of the surface of the body [5]. The shape of this component can vary based on what part of the body needs to be viewed and the design made to fit over it such as a knee or wrist joint, shoulder, the neck, or the head. A birdcage coil, for example, is one that encases the head to create an image of the brain and is named for its shape. A saddle shaped coil fits around the knee. The RF coil must be positioned perpendicular to the static magnetic field of the external magnet and its frequency depends on the field strength. The receiver processes signals ranging from 1MHz to 300MHz from at least six receiver coils in order to process them successively and quickly for the computer to construct the image [6].

3.0 Design

3.1 Cooling System

The use of superconducting magnets requires the material and coolant to be surrounded by a dewar, a structure of metal walls with a vacuum in between. The design of the dewar appears as concentric circles in around the closed bore; this can be seen in a cross section of the machine. The coolant in the dewar must be replenished by a refrigerator outside the magnet which pumps the helium down cooling pipes running from the refrigerator into a coldhead [3]. The system shown in Fig. 2 passes a cold water mixture around the gradient coils and magnet to remove the heat produced by the components [7].

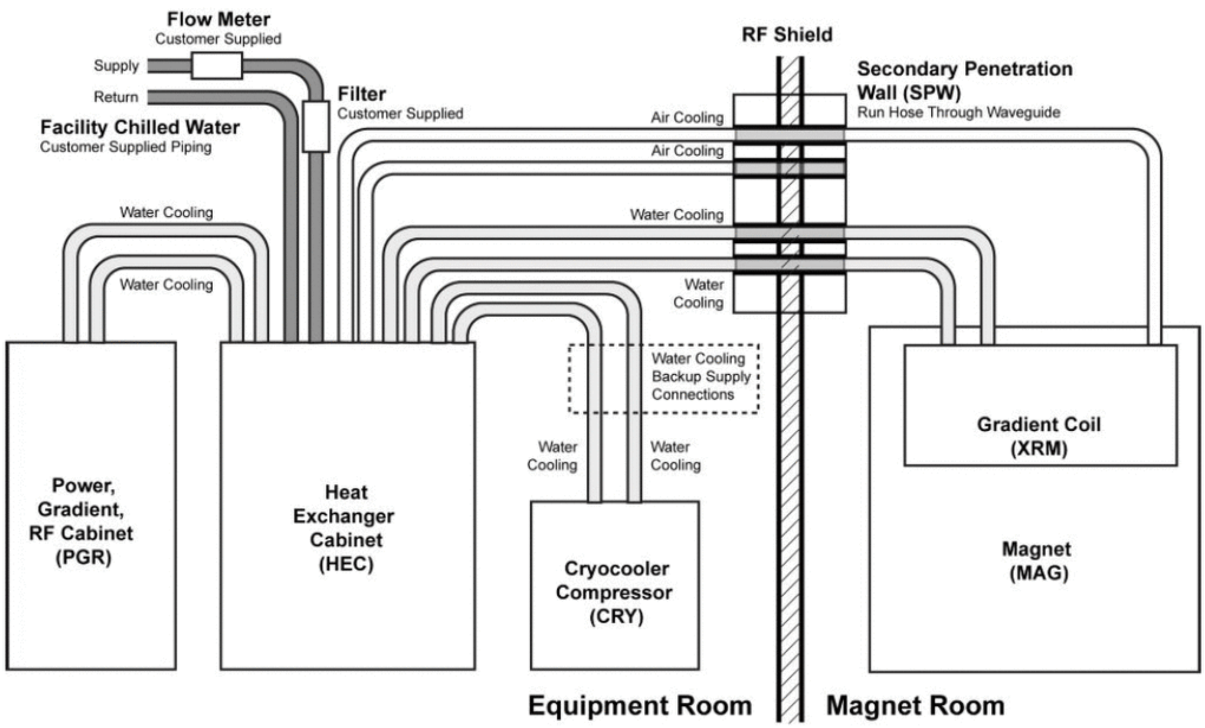

Fig. 2 MR System Water Cooling [7]

3.2 Magnetic Field

The magnetic field attracts ferromagnetic material like iron and nickel if it is strong enough and the objects are within the vicinity or inside the bore of the machine. The strength of the magnetic field produced by the external magnet varies by model and the type of imaging process, and it is uniform and static until manipulated. It is manipulated by the switching of the gradient coils on and off which function to create variations in the static magnetic field to focus the field on a particular section of the body. The dynamic changes of spatial distribution of the resulting field enables 3D changes of RF resonating absorption by the patient's tissues, and in consequence, the 3D imaging of the internal structure of the patient's body [8]. Magnetic field shielding reduces the reach of the fields and can make nearby metal objects less susceptible to the attraction, and both this and shimming lower the risk of unwanted variation in the fields. Shielding is done by introducing a ferromagnetic material to the outside of the external magnet that behaves as though to fence in the field from the environment. The fringe of the field is more drawn to the immediate conductor than anywhere else absent of one. In Fig. 3, the magnetic field formerly occupying the space labeled "Unshielded Field" is now restricted to the space between the two iron structures closer to the bore.

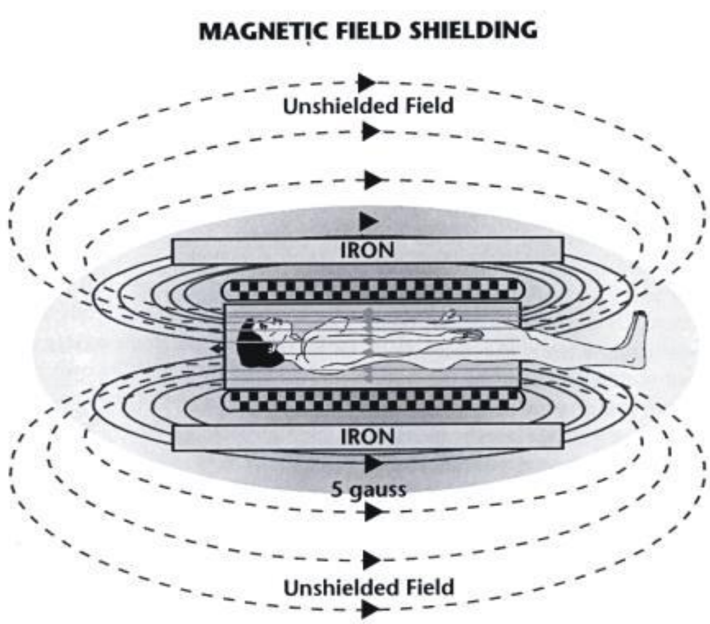

Fig. 3 Magnetic Field Shielding [5]

Since metal materials produce distortions in the magnetic field in or outside of the machine that impede imaging, this must be corrected with shims which adjust the electrical currents in the coils they are placed near [5]. Shimming can be done to amend the static magnetic field, the field produced by gradient coils or RF coils. Since a uniform static field is essential for the imaging process, metal shim coils are installed in the machine prior to the machine being used for examinations. In the examination room, sources of disruption to the magnetic field can still be present but the effects on the field reduced with shims and the main computer controls. The resonance frequency of the field can be measured and then the magnetic field mapped. The field is adjusted with shims until the desired field homogeneity is attained [4].

3.3 RF System

The radiofrequency system uses energy in a form of non-ionizing radiation. The RF coils produce energy pulses that are first transmit to the human body and are absorbed and then emitted. More specifically, the RF transmitter sends pulses in a range of frequencies that excite the nuclei of hydrogen atoms in body tissues. The image of body tissues formed by the computer is the information procured from the transmitting and receiving of signals, the nuclear magnetic resonance or NMR signals, by the coils. The differences in frequency signals received by the receiving coils come from the hydrogen atoms changing alignment with the static to gradient fields and back. They appear in the image as the forms of different body tissues [5, 6, 8].

4.0 Performance

The MRI process is begun from the computer console which controls the gradient field and RF pulse sequence and all other associated components functions. The patient, free of metallic material, lies on a table in the bore of the machine where the larger, static magnetic field aligns the body tissues’ hydrogen atoms. In essence, RF signals are transmit and received by the RF coils and the gradient coils locate the part of the body in space when rapidly switched on and off by the computer [2]. The hydrogen atoms are unaligned with the static field while this happens until the RF pulse is turned off and they are allowed to relax from their excited state and realign, and while doing so give off the NMR signal at varying frequencies. The NMR signal is converted into a digital signal then processed and presented as an image on the screen [9]. The diagram of Fig. 4 shows the MRI scanner system.

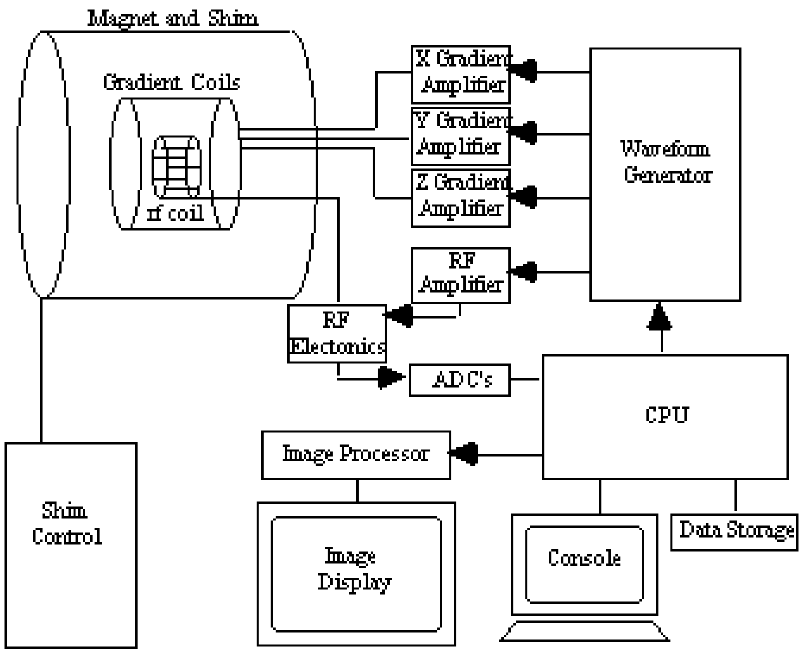

Fig. 4 MRI Scanner System [9]

Results of the MRI scan are monochromatic images of internal soft tissues. The patient may have had a contrast agent in them which increases the quality of the resulting images. Specialized applications of MRI can reveal neural activity in the brain, conditions of the arteries, tumor metabolism, and other information leading to the diagnosis of conditions of the body and brain disorders. Waiting for the scanning can be an inconvenience if the process takes up to an hour or two depending on the part of the body being scanned or if the patient moves and the process must be repeated.

5.0 Safety

There has been some debate and investigation on the safety of MRI scanners in a variety of situations, such as the effects of the strength of the magnetic field on the MRI clinical staff or on fetuses, neither of which are fully understood. In the case of superconductive or permanent magnets used in the scanners, there is always the risk of the field attracting metal objects in the vicinity. Objects pulled across the room into the bore can damage the machine, surrounding equipment, and people in its path. Patients with implants such as pacemakers or prostheses, or foreign metal objects such as shrapnel may experience the pull of the magnets to some degree. In addition, MRI workers, and even patients that repeatedly go in for examinations, are continually exposed to the static magnetic field by routine activities required by their occupational position, but there is usually little risk the weaker the strength of the magnetic field. The higher the field strength, the more risk MRI workers are exposed to. In one study, MRI workers reported signs, such as unusual physical sensations, that could draw up health concerns while working around a scanner with a magnetic field strength of 4.0 T or higher [10, 8]. Investigation of these health concerns are necessary before the introduction of higher magnetic field strengths which are shown to benefit the MRI environment or process, such as in regards to improving the quality of images. Based upon past and ongoing tests, doing so could increase health risks to those who are or will be greatly exposed to the field for a period of time. For now, limits and guidelines are placed on the type of external magnet and field strength delivered on the patients and staff, and the patients are made aware of potential risks until further study and conclusions can be made or design solutions be improved on.

Quenching is a concern when utilizing superconductive magnets in the scanner. A quench is the loss of superconductivity of the coils. This could happen if a large magnetically susceptible object disrupts the magnetic field or a large amount of heat produced by the current and rapid boiling off of cryogens [2]. The gas produced is usually able to be vented out of the room but should it come into contact with people it could result in a health hazard.

6.0 Improvements

Over the years MRI scanner model designs were innovated to reach greater magnetic field strengths, which in turn sped up the scanning process, created better image quality, and started research into more medical opportunities for MR devices, although challenges surrounding those topics exist. Researchers look into the possibility of the combination of similar devices with the MRI like the PET scan to better attend to patients' needs.

Recent developments in MRI technology implement nonmagnetic robotic devices in MRI to operate in the magnetic fields and not distort or otherwise interfere with imaging. If properly designed the robots could make real time surgeries with MR imaging possible and further be used as devices to offer more methods of rehabilitation and therapy to the patients and expand on rehabilitation research. Fluid power systems would be the best solution to replace the usual electromagnetic motors to run the robots. Pneumatic, MRI-guided robots controlled by clinicians could give them more access to patients inside the bore where they are otherwise restricted from them. In this way the accuracy of MR imaging and the precision of robotics could be taken advantage of to perform precise and less invasive surgeries where the MRI scanning is carried out in real time [1].

Earlier designs of scanners with superconductive magnets used liquid nitrogen as the cryogen, but later models moved toward replacing liquid nitrogen with liquid helium. However, it is a scarce resource and the dewar requires 1,700 liters to circulate cool temperatures around the coils. Future designs of MRI plan to reduce the requirement of 1,700 liters of liquid helium or to completely replace the liquid helium with an alternative. This would also eliminate the safety hazard of the coolant being released into the air from the machine if quenching occurs.

Research has gone into the design of MRIs to effectively reduce the structural-acoustic noise produced by the vibrations of the gradient coils, as less noise would add to patient comfort. These noise levels partially depend on the strength of the main magnetic field and its interaction with the gradient coils [11]. To acquire an image from the scanning and by altering the imaging parameters, the current in the gradient coils is rapidly switched on and off. This causes vibrating of the coils and surrounding components and is audibly heard as loud knocks or tapping in a sequence [10, 11]. Before inducing high magnetic field strength, potential hearing risks should be taken into account and also the methods by which the noise could be reduced. Investigations of active noise control methods include creating a zone of destructive interference, but this is more effective at low frequencies than high frequencies. Micro-perforated panels made out of absorbing material lining the bore and gradient coils may be more effective in stiffening the coils and absorbing the noise at greater frequencies. The gradient coils themselves could be revised to a quieter design [12].

7.0 Conclusion

MRI technology makes use of conductive material as an integral part of its basic components and the positioning of coils in the manufacturing stage, tuning of magnetic fields, and scanning process regulated by a central computer unit in the overall design to fulfill its function of acquiring images of structures and processes in the human body. By efforts made to further develop the design of the scanner, modern MRI machines have been engineered to operate more efficiently and safely to benefit both patients and clinicians.

References

[1] J. Ueda, D. B. Comber, J. Slightam, M. Turkseven, V. Gervasi, Webster,Robert J., I.,II and E. J. Barth. MRI - compatible fluid-powered medical devices. *Mech. Eng.135(6),* pp. S13-S16. 2013. Available: http://library.collin.edu/login?url=http://search.proquest.com.library.collin.edu/docview/1371830309?accountid=7969.

[2] Bruno Di. Muzio and J. Ray Ballinger. *MRI (introduction)*. 2005-2016. Retrieved from https://radiopaedia.org/articles/mri-introduction, [Sept. 30, 2016].

[3] J. P. Hornak. *The Basics of MRI*. 1996-2014. Retrieved from https://www.cis.rit.edu/htbooks/mri/chap-9/chap-9.htm, [Sept. 30, 2016].

[4] *Secondary Magnetic Resonance Imaging Magnets*. 2016. Retrieved from http://radiologykey.com/secondary-magnetic-resonance-imaging-magnets/, [Oct 8, 2016].

[5] Perry Sprawls*. Magnetic Resonance Imaging*. Retrieved from http://www.sprawls.org/mripmt/MRI02/index.html, [Oct. 8, 2016].

[6] John Scampini. *Introduction to Magnetic Resonance Imaging (MRI)*. 2010. Retrieved from https://www.maximintegrated.com/en/app-notes/index.mvp/id/4681, [Oct 8, 2016].

[7] *MR System layout*. 2016. Retrieved from http://mri-q.com/mr-system-layout.html, [Oct 9, 2016].

[8] J. Karpowicz, M. Hietanen and K. Gryz. Occupational risk from static magnetic fields of MRI scanners. *Environmentalist 27(4),* pp. 533-538. 2007. Available: http://library.collin.edu/login?url=http://search.proquest.com.library.collin.edu/docview/221753456?accountid=7969. DOI: http://dx.doi.org.library.collin.edu/10.1007/s10669-007-9064-1.

[9] Stuart Clare. Functional *MRI: Methods and Applications*. 1997. Retrieved from https://users.fmrib.ox.ac.uk/~stuart/thesis/chapter_2/section2_6.html, [Oct 8, 2016].

[10] O. Coskun. Magnetic resonance imaging and safety aspects. *Toxicol. Ind. Health27(4),* pp. 307-13. 2011. Available: http://library.collin.edu/login?url=http://search.proquest.com.library.collin.edu/docvie

w/863933080?accountid=7969. DOI:
http://dx.doi.org.library.collin.edu/10.1177/0748233710386413.

[11] G. Li and C. K. Mechefske. Structural-acoustic modal analysis of cylindrical shells: Application to MRI scanner systems. *MAGMA 22(6),* pp. 353-64. 2009. Available: http://library.collin.edu/login?url=http://search.proquest.com.library.collin.edu/docview/207695203?accountid=7969. DOI: http://dx.doi.org.library.collin.edu/10.1007/s10334-009-0185-z.

[12] G. Li and C. K. Mechefske. A comprehensive experimental study of micro-perforated panel acoustic absorbers in MRI scanners. *MAGMA 23(3),* pp. 177-85. 2010. Available: http://library.collin.edu/login?url=http://search.proquest.com.library.collin.edu/docview/365816423?accountid=7969. DOI: http://dx.doi.org.library.collin.edu/10.1007/s10334-010-0216-9.