AAPM REPORT NO. 20

SITE PLANNING FOR MAGNETIC RESONANCE IMAGING SYSTEMS

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REPORT OF AAPM
NMR Task Group No. 2*

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CONTENTS

I INTRODUCTION AND MR SYSTEM DESCRIPTION

A. Introduction

The planning of Magnetic Resonance (MR) imaging facilities continues to offer challenging opportunities for creativity and courage. Siting practice is changing rapidly as MR systems evolve and as more understanding and experience are accumulated. Some relatively recent siting decisions have been overly costly or have produced unnecessary inconvenience in patient management. A growing consensus is developing, however, on the ranges of practical solutions to the many requirements of MR site planning, with magnetic field containment and RF shielding being foremost among these.

Site selection and preparation for a clinical MR installation require special considerations that have not been encountered previously in a clinical environment. The factors involved in locating an MR unit in a diagnostic facility are more numerous and far more complex than for radiological imaging equipment. In addition to the usual requirements for an appropriate foundation and structure, the effects of the surrounding structure on magnetic field uniformity and the effect of the magnet’s fringe fields on other devices must be considered. The radiofrequency (RF) signals from the MR installation may affect equipment in adjacent facilities and electronic devices worn by patients in the MR facility or nearby areas. Conversely, and more likely, the RF radiation in the environment can have detrimental effects on the operation of the MR imager. There may also be consequences of locating two MR systems in the same vicinity. Patient medical emergencies during imaging and potential malfunctions such as magnet quenching require special considerations not usually encountered in a medical facility. Present knowledge in all these areas is both limited and dispersed.

Suppliers of MR systems have gained considerable expertise in many aspects of site planning and installation. However, the medical physicist can contribute significantly to planning and operation of an MR facility. The physicist’s involvement can often reduce siting costs, prevent irreversible mistakes and promote maximum utility and flexibility in the clinical operation of the imager. By being involved in the early planning stages, the physicist can direct the decision process effectively and help evaluate potential machines and sites as well as architectural firms, before any commitments are made. The physicist’s overall knowledge places him in a unique position to interface between all parties involved and optimize the design, construction and operation of an MR imaging facility.

A task group under the Nuclear Magnetic Resonance Committee of the American Association of Physicists in Medicine was formed to assemble information currently available, follow technical developments, gather results and experiences from recent installations and suggest areas for further investigation on site planning for MR imaging systems. The task group is making this information available to the medical and manufacturing communities in the form of this report which will be updated and expanded as more knowledge and experience are gained in this rapidly changing area. Close liason has been maintained with the ACR MR Committee on Imaging Technology and Equipment.

B. System Components and Physical Specifications

The major sections of an MR imaging system are listed in Table I-1. A general discussion of the different features of these sections is given in Chapter 10 of (1). See also the Report of AAPM NMR Task Group No. 6, Systems Components for Consideration and Purchasing an NMR Imager (2).

TABLE I-1

GENERAL FEATURES OF MR IMAGING SYSTEMS

1. MAGNET SYSTEM
    - Static field generation coils
    - DC power supply
    - Cooling system
    - Active and passive shimming mechanisms
    - Gradient coils - x, y, z sets
    - RF coils (transmit and receive)
    - Patient handling
2. RADIOFREQUENCY SYSTEM
    - Stable RF source (synthesizer)
    - Transmitter (pulse forming circuitry)
    - Receiver (amplification and demodulation)
3. GRADIENT SYSTEM
    - Waveform generation
    - Power amplifiers
4. DATA ACQUISITION, TIMING AND CONTROL SYSTEM
5. COMPUTER AND DISPLAY SYSTEM

The block diagram in Fig. I-1 shows typical interaction pathways between the major sections of an MR imaging system (3).

At the present time a wide range of magnetic field strengths is available. Table I-2 shows some typical magnetic field strengths available commercially, ranging from 0.02 Tesla to around 15 Tesla. For a brief discussion of different imaging magnets see (4). General information on site planning and MR imaging can be found in (6, 7 and 9).

Physical specifications for the various components of different imaging systems are best obtained from the manufacturers. For illustration purposes, typical components with their sizes, weights and power consumption are listed in Table I-3.

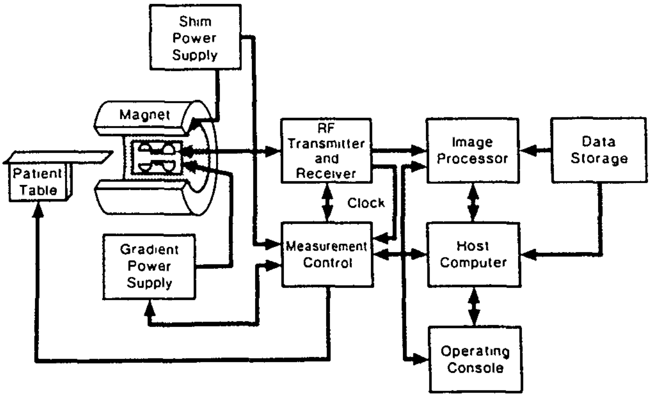


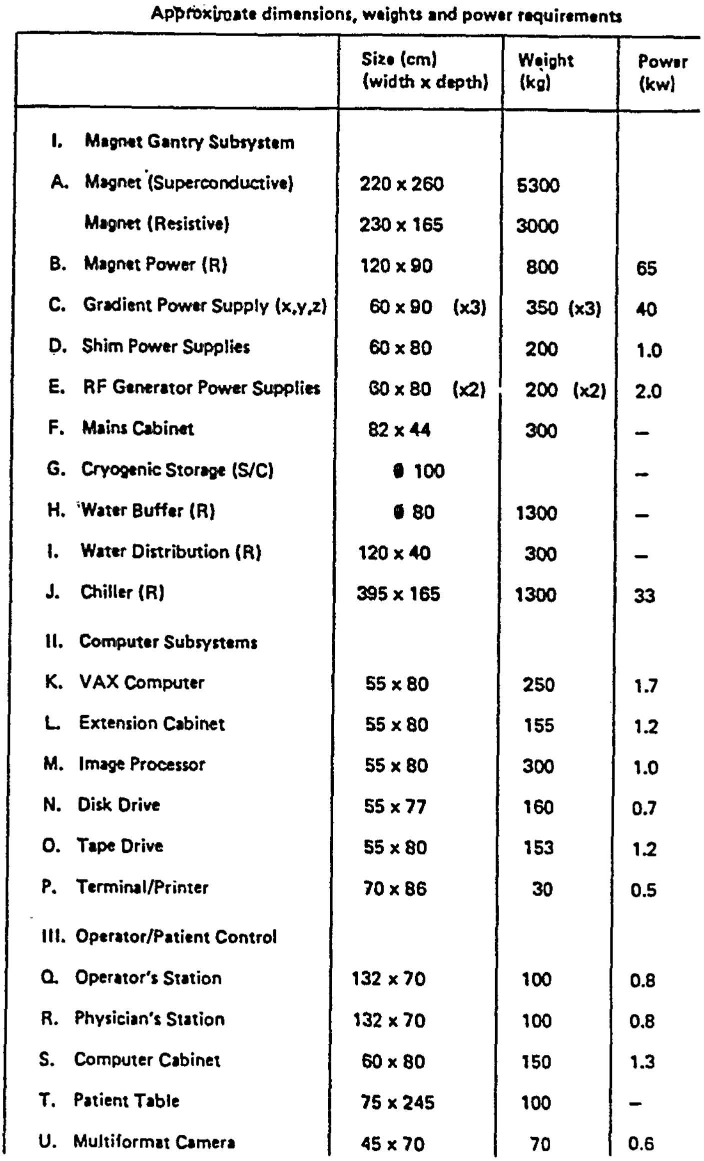
Figure I-1 Block diagram of an MR imaging system (3).

TABLE I-2

MAGNET TYPES AND TYPICAL FIELD STRENGTHS IN TESLA (T) FOR MEDICAL APPLICATIONS

Air Core Resistive - Large Bore Imaging	0.02 - 0.2 T
Iron Core Resistive - Large Bore Imaging	<0.5 T
Superconducting - Large Bore Imaging	0.15 - 2.0 T
Superconducting - Medium bore (imaging research)	2.0 - 5.0 T
Superconducting - Small Bore Spectrometer	1.5 - 15.0 T
Permanent	< 0.4 T
Hybrid (combination of permanent and resistive)	< 0.4 T

TABLE I-3
TYPICAL COMPONENTS AND THEIR PHYSICAL REQUIREMENTS FOR 0.15T RESISTIVE AND 0.5T SUPERCONDUCTING SYSTEMS. FROM AN EARLY PHILIPS SITE PLANNING GUIDE (5).



Approximate dimensions, weights and power requirements

	Size (cm) (width x depth)	Weight (kg)	Power (kw)
I. Magnet Gantry Subsystem			
A. Magnet (Superconductive)	220 x 260	5300	
Magnet (Resistive)	230 x 165	3000	
B. Magnet Power (R)	120 x 90	800	65
C. Gradient Power Supply (x,y,z)	60 x 90 (x3)	350 (x3)	40
D. Shim Power Supplies	60 x 80	200	1.0
E. RF Generator Power Supplies	60 x 80 (x2)	200 (x2)	2.0
F. Mains Cabinet	82 x 44	300	–
G. Cryogenic Storage (S/C)	Ø 100		–
H. Water Buffer (R)	Ø 80	1300	–
I. Water Distribution (R)	120 x 40	300	–
J. Chiller (R)	395 x 165	1300	33
II. Computer Subsystems			
K. VAX Computer	55 x 80	250	1.7
L. Extension Cabinet	55 x 80	155	1.2
M. Image Processor	55 x 80	300	1.0
N. Disk Drive	55 x 77	160	0.7
O. Tape Drive	55 x 80	153	1.2
P. Terminal/Printer	70 x 86	30	0.5
III. Operator/Patient Control			
Q. Operator's Station	132 x 70	100	0.8
R. Physician's Station	132 x 70	100	0.8
S. Computer Cabinet	60 x 80	150	1.3
T. Patient Table	75 x 245	100	–
U. Multiformat Camera	45 x 70	70	0.6

II FACILITY LAYOUT

A. General

The MR facility must be designed within the constraints inherent in the technology of MR imaging. Magnetic fringe fields and cryogen storage are typical examples of the special considerations which must be made. Some differences do exist between various MR imaging systems, mainly due to magnet design. In particular, permanent and iron core resistive magnets have a much smaller fringe field region than air core electromagnets of similar field strength. A discussion of permanent magnet installation is given in (10).

As a starting point, Figure II-1 lists some ideas on creating an ideal environment for magnetic resonance imaging. This information from an early General Electric Planning Guide (II), illustrates the breadth of detail involved in planning an MR imaging site.

The basic layouts of magnet installations do not usually differ drastically between different manufacturers who provide site planning guides (5, 11, 12, 13, 8, 14, 28, 48) listing the physical specifications of their equipment. The major factors influencing layout are magnet type, field strength and the type of building available or planned for the MR imaging area. Figure II-2 shows several possible layouts as examples.

Technicare has used the concept of four different zones to define various regions of the magnetic fringe field (Figure II-3 (14)). Zones 1, 2, 3 and 4 are defined as >l.5 mT, 0.5 to 1.5 mT, 0.2 to 0.5 mT and 0.1 to 0.2 mT, respectively. Different types of equipment or activity can then be permitted within these zones. For example, public access to zone 1 is usually restricted.

The magnet area must be properly secured with locked entrances to keep out unauthorized persons and particularly to prevent inadvertent introduction of potentially hazardous metallic objects. The design of the area must also provide adequate venting in the event that a superconducting magnet should quench. These and other health and safety aspects are discussed in subsequent sections and in the referenced publications..

The current state of technology indicates that the following guidelines will lead to the construction of an environment that will promote optimal MR performance and minimize the system's interference with other equipment.

Construction materials

To maintain magnet field homogeneity, the following specifications for materials are recommended:

Floor The floors should be poured slab on grade with fiberglass-impregnated or epoxy-reinforced concrete. Reinforcing bars or corrugated iron sheets should be avoided if possible, especially within the 50 gauss line.

Walls. The walls should be concrete with minimum steel reinforcement or constructed of wood with standard nails, consistent with the national building code, Section 360.2.

Electrical conduit. Electrical conduit within 25 ft. (7.6 m) of magnet isocenter must be PVC or aluminum. in any case, do not use ferromagnetic material inside the exam room, since it could inadvertently become a projectile.

Plumbing pipes and drains. Pipes and drains within 25 ft. (7.6 m) of magnet isocenter must be of nonferrous material such as PVC, copper or brass. Again, do not use ferromagnetic material inside the exam room.

Electrical and mechanical considerations

HVAC. Heating, ventilation and air conditioning equipment should not be located in the area inside the 10 gauss line.

Transformers. Do not locate electrical distribution transformers inside the 3 gauss line.

Floor concrete. The finished layer of floor concrete should not be poured until the specific MR magnet/computer system is chosen. Final cable requirements and associated ducts will be specific to the particular type of system installed.

Superconducting magnet requirements

Venting for cryogen exhaust should be aluminum ducting capable of 350 ft.^{3}/min. (9.9 m^3/min.)--e.g., one 6-in. (15.24 cm) and one 2-in. (5.08 cm) nonmagnetic vent pipe which is electrically isolated at the penetration points.

A loading dock platform should be accessible to the magnet room for delivery of liquid helium/liquid nitrogen dewars. The loading platform should be placed beyond the 3 gauss line. Without a loading dock, a forklift truck will be needed for unloading the dewars.

General siting concerns

Exit from the magnet room should allow for rapid patient removal from the magnetic field to an area where patient monitoring and life support equipment will operate satisfactorily in case a medical emergency occurs.

Physical access shouldbe provided to the room for placement of the magnet.

A metal detector should be used to screen for any ferrous objects on patients and medical personnel. Small ferrous objects can become dangerous projectiles in regions of high magnetic field gradients within 6.5 ft. (2 m) of the magnet.

RF shieldlng requires a minimum attenuation level of 100 db for electrical/plane waves in the frequency range of 10 KHz to 100 MHz.

Figure II-1 Ideas on creating an ideal environment for magnetic resonance imaging. General Electric Site Planning Guide, 1984 (11).

TYPICAL 0.15T RESISTIVE SYSTEM (IN HOSPITAL SITE) 1,450 SQ. FT.

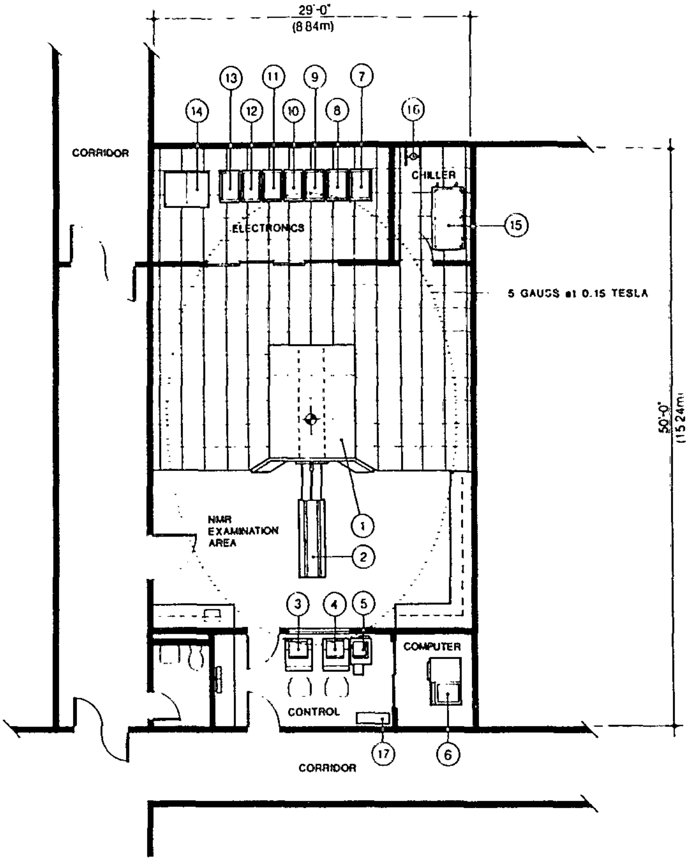


Figure II-2 Typical Magnet Installations from the Picker Site Planning Guide (13).
(a) Typical 0.15 T resistive system layout.

TYPICAL 1.0T MRI FACILITY (STAND ALONE) 4,458 SQ. FT.

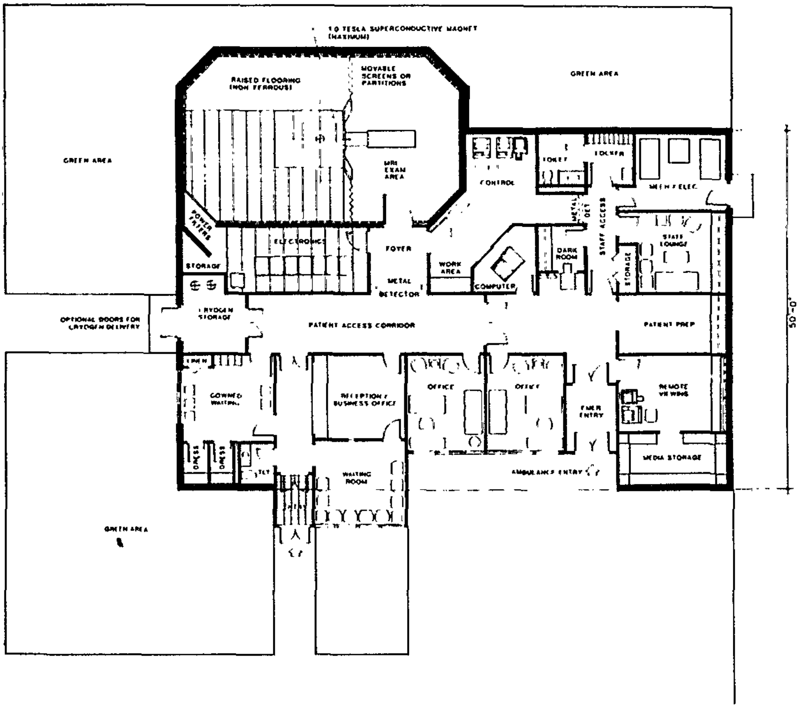


Figure II-2 (b) Typical 1.0 T layout.

TYPICAL MR/CT IMAGING FACILITY (MAGNET SIZE - 1.0T to 2.0T) 4,772 SQ. FT.

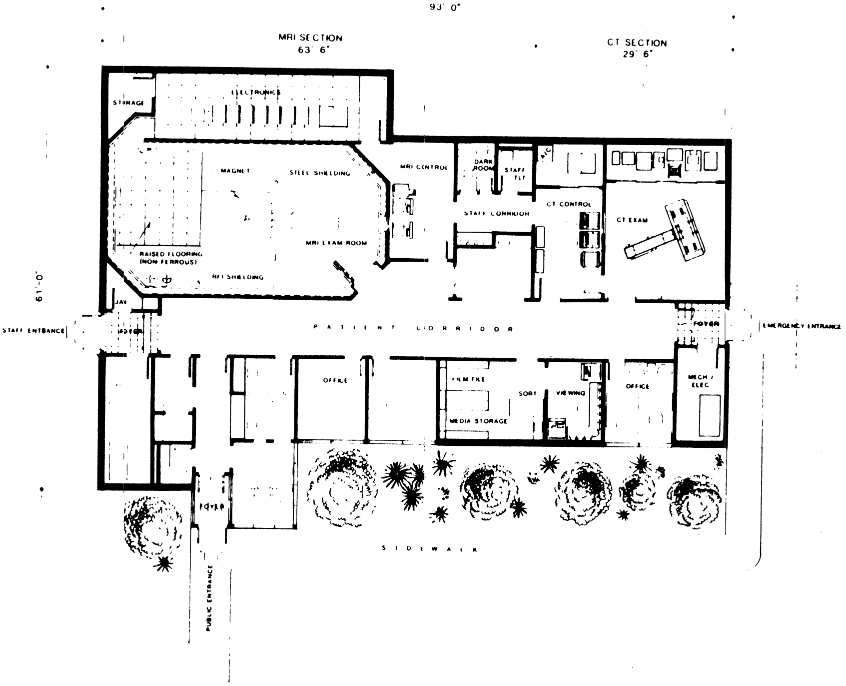


Figure II-2 (c) Typical 1.0 to 2.0 T MR imager layout with accompanying CT facility.

ZONE DIMENSIONS

	(Meters)			
	0.60 Tesla		1.5 Tesla	
	Bore	Side	Bore	Side
Zone 1	6.3	4.8	8.7	6.8
Zone 2	9.0	7.0	12.2	9.9
Zone 3	12.3	9.6	16.5	13.0
Zone 4	15.5	12.1	21.0	16.5
	(Feet)			
	Bore	Side	Bore	Side
Zone 1	21	16	29	22
Zone 2	30	23	40	33
Zone 3	40	32	54	43
Zone 4	51	40	69	54

Figure II-3 Zone dimensions for Technicare 0.6 T and 1.5 T superconducting magnets (14). Zone 1 is > 1.5 mT, Zone 2 is 0.5-1.5 mT, Zone 3 is 0.2-0.5 mT and Zone 4 is 0.1- 0.2 mT.

B. Operational Considerations

Many operational considerations for MR imaging are similar to those for CT. Differences occur because of fringe magnetic fields, radio frequency shielding, geometry of the magnet bore, and lack of known biological hazard with MR imaging. Nevertheless, a patient's condition can deteriorate during MR imaging, requiring emergency intervention. MR imaging systems can interfere with both patient monitoring and cardiopulmonary resuscitation. Appropriate architectural and administrative measures can lessen these difficulties.

The long, narrow magnet bore makes it difficult to observe the patient. Locating the operating console near the axis of the magnet provides a better, although still limited, view of the patient being scanned. Fringe magnetic fields may require location of the console relatively distant from the magnet. Magnetic shielding of the video display unit in the console can allow placement closer to the magnet.

The window between the magnet room and control or console room usually requires RF shielding, which is often two layers of copper screen or perforated sheet. This shielding reduces patient visibility by light attenuation and by the distracting effect of Moire patterns and reflections. These problems can be reduced by appropriate window selection and attention to lighting details. Charge-coupled device (CCD) television cameras can be operated in relatively high magnetic fields and can be quite helpful in patient monitoring. Medical personnel and/or family members can remain near the patient to monitor or reassure the patient.

The magnetic field within the scanner can affect or limit the performance of patient monitoring and communication equipment. For example, the magneto-hydrodynamic effect from flowing blood distorts electrocardiographic signals. Various solutions are being developed for these problems, such as using the main magnetic field as the field for a speaker or piping in sound via airline style head phones or providing a pneumatic squeeze bulb as a call button for the patient. Interfacing these devices with external systems is sometimes difficult.

The operation of patient support equipment such as respirators, and infusion pumps can be affected near some types of magnets and other equipment such as stretchers, oxygen tanks and intravenous (IV) poles may be subjected to strong attractive forces near the magnet bore. These problems and difficulties with monitoring will make some patients inappropriate candidates for MR imaging until better solutions are found.

Cardiopulmonary resuscitation (CPR) is severely limited adjacent to some magnets because of the possible malfunction of CPR equipment in high fringe fields and the danger of ferromagnetic objects brought by the resuscitation team being attracted toward the magnet. The screening of arriving personnel for ferromagnetic objects is, of course, impossible. The usual solution is to remove the patient, by means of a non-ferromagnetic stretcher stationed in the scan room, to an area where CPR can be carried out. This area might be equipped with an emergency cart, monitors, oxygen and suction. Coordination of this phase of the design with the hospital’s CPR committee may be helpful. Means of preventing other personnel, who have responded to the emergency, from wandering into the magnet room during the activity surrounding CPR, should be considered. Useful means include distance, doors, warning signs and administrative procedures, such as training of the CPR team or assigning a member of the MR Imaging staff to close the magnet room door. Such situations necessitate a means of emergency shut down of the magnet.

Claustrophobia and other forms of anxiety may interfere with imaging as well as patient comfort. Helpful solutions include good patient preparation, communication during scanning, someone remaining with the patient during scanning, disguising the intimidating appearance of the magnet, hiding the computer room from patient view, use of warm architectural finishes, keeping the magnet room size undramatic, disguising the vault-like appearance of the RF-shielded door, and making safety procedures and warning signs as unthreatening as possible, consistent with adequate protection. The warm appearance of carpet must be weighed against the durability and maintenance advantages of traditional floors.

Controlled access to the MR Imager suite is necessary because of possible harm to people with ferromagnetic medical implants and harm to people and equipment from unrestrained ferromagnetic objects in the vicinity of the magnet. A single entrance to the suite is helpful in this regard. Provision must be made for housekeeping personnel with floor polishers, for security personnel with keys, radios and guns, and for firemen with air tanks and axes. Non-ferromagnetic mops and buckets in a special closet or a built-in vacuum cleaner with plastic implements can be supplemented by direct supervision and/or training. If a special lock on the magnet door, which is not part of the hospital master key system, is used, emergency access to the key will be required.

C. Multiple System Facilities

Magnets now can be shimmed for operation in close proximity to one another. Even without magnetic shielding, it is feasible to place 1.5 T magnets as little as 25 feet apart. Such close placement generally has the disadvantage that removing the field from one magnet, or adjusting it significantly, necessitates reshimming of the second magnet. This problem might be solved by determining in advance fixed locations for metal shim pieces or fixed settings for shim coils for the two cases when the adjacent magnet is or is not energized.

A wide variety of magnet orientations is now possible as well. If the magnet axes are perpendicular to each other (location A in Figure II-4) the inhomogeneity induced in one magnet by the other is actually reduced compared with the case in which the two magnet axes are parallel (location B). This is true in spite of the fact that the absolute field is greater for the perpendicular case than for the parallel case at the same center to center distance.

Since shimming can now be performed relatively easily, the more significant constraint is the force between the magnet coils and the torques on the coils. Placement of two systems in a symmetric (parallel or antiparallel) orientation results in zero torque, with the distance between magnets being set by the maximum allowed force between the coils (15).

The differences between various magnet orientations and separation distances are slight within the relatively liberal constraints of mutual torques and forces mentioned above. It is probably best to design adjacent magnet locations to optimize operational efficiency and flexibility, within the overall constraints of magnetic field containment discussed earlier. A convenient design for a two system facility probably includes common operation and image interpretation areas sufficiently spacious to provide ample magnet separation (see Figure II-2 (c)). This arrangement can minimize the time required to reshim the second system if the first must be shut down for some reason.

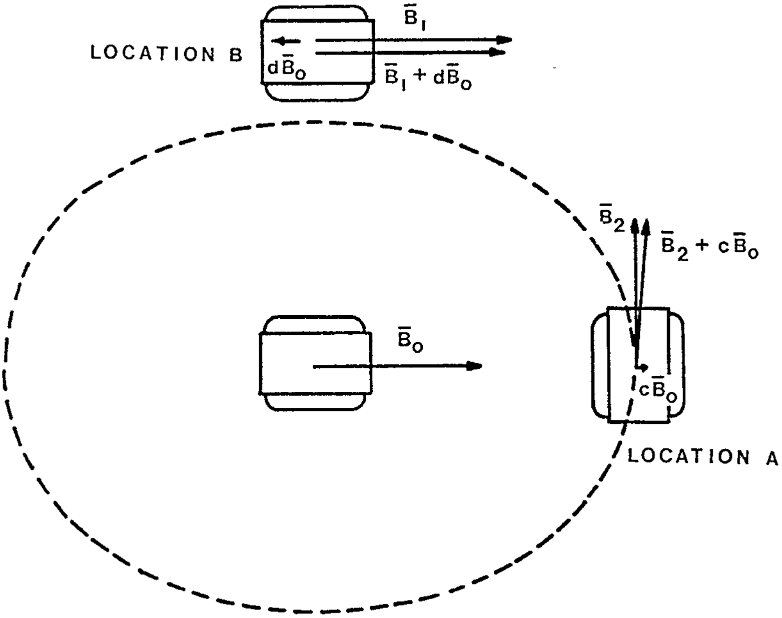


Figure II-4 Typical inhomogeneity considerations for two-magnet facilities. For the same magnet-to-magnet separation, location A has a larger resultant field ($B_2 + cB_0$) and better uniformity than location B.

III HEALTH AND SAFETY CONSIDERATIONS

A unique feature of MR imaging is the presence of the high magnetic fields produced by large magnets. The major safety consideration is simply the development of administrative and physical barriers to prohibit the accidental introduction of ferromagnetic objects into the magnet room (16). Conventional IV poles and wheelchairs are usually attracted toward the magnet and larger ferrous objects such as oxygen tanks and floor polishers can be attracted to the magnet with such force that they become difficult to restrain. In addition, image distortions can result from small ferrous objects either on patients or accidentally introduced and clinging to the inside bore of the magnet. For these reasons the magnet area should be secured against unauthorized entry at all times. At reasonable distances from air-core resistive and superconductive magnets the field falls off according to the dipole approximation at approximately $1/r^3$. Large distances are necessary, however, before the fringe field is reduced below the earth's magnetic field (~0.05 mT).

Various recommendations for access control and labeling of fringe fields have been made. At fields greater than 1.5 mT, areas can be designated by signs reading "CAUTION - HIGH MAGNETIC FIELD" (17). Fields greater than 1.5 mT are not far from the range at which ferrous objects can be pulled toward the magnet (see Figure III-1) and many medical devices may not operate properly, including a small fraction of cardiac pacemakers (18). In fact, for safe operation of all pacemakers, a 0.5 mT limit has been recommended (19). A "CAUTION - MAGNETIC FIELD" warning can be specified for the area between 1.5 and 0.5 mT. Within this region, administrative controls for excluding patients with pacemakers can be applied and the movement of large ferrous objects can be controlled. Individuals wishing to enter the magnet room should pass through this administratively controlled area to ensure the removal of credit cards, watches, and loose ferrous objects. For magnetic fields less than 0.5 mT no administrative controls are necessary and little possibility exists for health and safety problems.

Fringe fields can be substantially decreased through the use of magnetic shielding. Shielding of magnets has the advantage of reducing the controlled space required around the magnet or magnet room. As discussed in Section V, numerous electronic devices found in a hospital imaging department (eg, x-ray tubes, CRT's, scintillation cameras, and image intensifiers) may be affected by magnetic fields of the order of 0.1 to 5 mT. Siting an MR unit in an area in which fringe fields impact on these devices may require shielding of the magnet. Such shielding can simplify the problems of controlled access for safety reasons (16).

Approximate calculations, using a dipole to simulate the fringe field of a magnet, can be helpful in understanding the magnet's pull on ferromagnetic objects. A typical 1.0 T imaging magnet has a field of 0.5 mT at an axial distance of ten meters from the magnet center. This yields an equivalent dipole strength of 1.99 Tesla-meter^3. The fringe field of such a dipole is shown in Figure III-1. The outline of the magnet housing is shown to suggest the limits of validity of this approximation.

If a ferromagnetic object is allowed to rotate so that its induced dipole moment is parallel to the applied field, the attractive force, F, is given by

$$F = M \cdot |\text{grad } B| \, , \qquad (1)$$

where M = magnitude of the induced dipole
and B = magnitude of the magnetic field.

The simplest case for computing the induced dipole moment is that of a long slender object, aligned with the field. Assuming that the flux is concentrated in the object and the iron is saturated produces the maximum dipole moment and, therefore, the maximum force per unit mass of iron. The dipole moment per unit volume of saturated iron is approximately 1.6 x 10^6 amp-turn.m^{-1}. Introducing this, and the density of iron, into Eq. (1) permits calculation of lines of constant force per unit mass as shown in Figure III-1. This force varies inversely with the fourth power of the distance along the axis of the magnet as shown in Figure III-2. In the case of fixed magnet geometry, the force at any position scales linearly with the strength of the magnet. Because some objects may not fully saturate, this calculation can overestimate the actual force.

A solid sphere of iron has the smallest induced dipole moment and, therefore, the minimum force per unit mass of iron (assuming a freely rotatable object). Its dipole moment is

$$M = \frac{4\pi R^3 B}{\mu_0} \, \frac{|\mu/\mu_0 - 1|}{|\mu/\mu_0 + 2|} \qquad (2)$$

where R = radius of the sphere,
μ = permeability of iron, and
μ_0 = permeability of free space.

Since m is much greater than m_o, the term in brackets is approximately equal to unity. Combining Eqs. (1) and (2) with the density of iron yields a lower limit on the force per unit mass of iron, which is shown in Figure III-2. At a fixed position, it scales as the square of the magnet’s central field. Equally important, this force varies inversely with the seventh power of distance, which explains why one can be fooled by the sudden increase in force on iron as it is brought near the magnet!

Complex ferromagnetic objects will have their force versus position curves between the two extremes shown in Figure III-2. At short distances and high fields, the gap between the two curves narrows as the sphere approaches saturation. In Figure III-3, the gap between the two limiting cases is shown for a force equal to one tenth the weight of the iron. Unless there is a strong reason to do otherwise, the fully saturated case, together with an appropriate value for the force, should probably be used to calculate safety limits.

Additional administrative controls that can be adopted for the elimination of safety problems associated with the fringe fields of large magnets include locking the magnet room when it is not in use and the careful screening of individuals entering the magnet room. Metal detectors do not seem to be as effective as alert, personal screening; thus, all entry to the magnet room should be routed through the operator area. The movement of patients should be designed to ensure that the operator has control over screening for unauthorized entry/exit as well as the presence of cardiac pacers, aneurysm clips, and aortic heart valves. Additionally, the movement of ancillary medical personnel into the restricted area must be controlled and the location of doors and operator areas should facilitate this control.

A practical problem that exists with the use of superconducting magnets is the requirement for the replenishment of liquid nitrogen (-196°C) and liquid helium (-269°C). A dedicated coolant line can sometimes be incorporated in the planning of the facility. Alternatively, replenishment can be made via the use of dewars which can weigh as much as 500 lbs. Cryogen recovery systems are often utilized in facilities that have a large use of He and N. With lower consumption of cryogens as is typical for imaging systems, a recovery system is seldom economical.

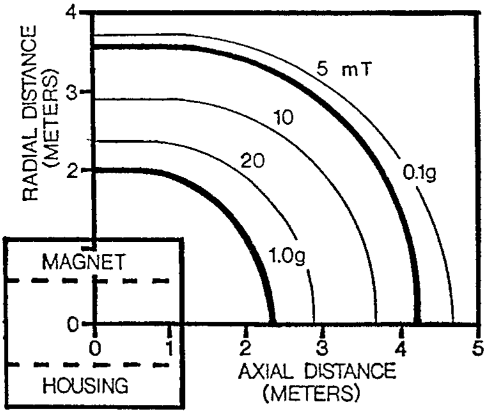


Figure III-1 Lines of constant force per unit mass of magnetically saturated iron for the force equal to the weight of iron (1.0g) and one tenth the weight (0.1g). Based on a dipole simulation of a 1.0T imaging magnet. Lines of constant magnetic field strength are shown.

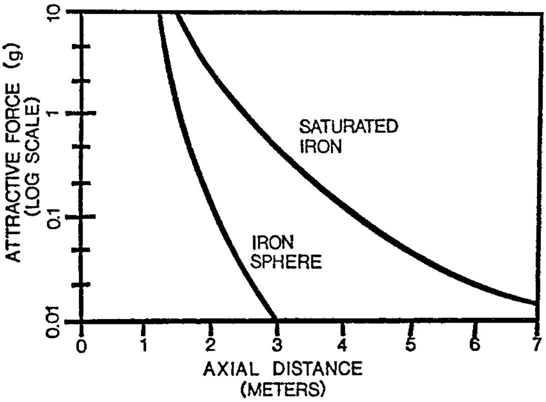


Figure III-2 Force per unit mass of iron along the central axis for saturated iron and for an unsaturated iron sphere. Based on a dipole simulation of a 1.0 T imaging magnet.

A small amount of helium and nitrogen gas is continuously discharged from a superconducting magnet. This can be vented using the room air handling system. In the event of an incident causing major loss of coolant (quench) a discharge pipe for the rapid removal of gas is necessary. A quench which results in a complete loss of coolant (1200 to 1500 liters) can supplant breathing air in the magnet room unless such a discharge pipe is provided. Oxygen monitoring should be provided as a safety measure in the magnet room.

Table III-1 lists MR safety-related guidelines from the FDA, Division of Radiologic Health (DRH), the British National Radiologic Protection Board and the Canadian Environmental Health Directorate, Health Protection Branch. It does not appear that the fields from MR imagers represent a health hazard at levels below these guidelines.

TABLE III-1

ELECTROMAGNETIC SPECIFICATIONS RELATED TO PATIENT SAFETY

Field Property	Units	DRH Guidelines (1982)	NRPB Guidelines (1980)	HPB Guidelines (1986)
STATIC B FIELD	TESLA	2.0	2.5	2.0
RATE OF B FIELD CHANGE	T/s	3	20 (if ≥ 10ms)	3
SPECIFIC ABSORPTION RATE (SAR)	W/kg			
BODY AVERAGE		0.4	(1°C Rise)	(0.5°C Rise)
HEAD AVERAGE		0.4	(1°C Rise)	(1.0°C Rise)
PEAK		2.0		

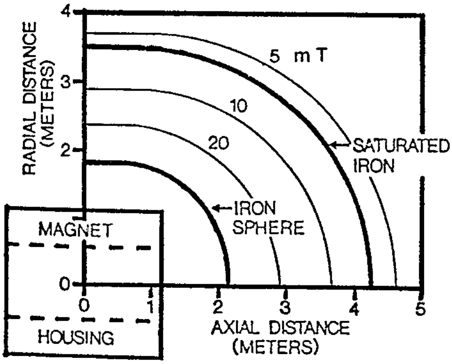


Figure III-3 Lines of constant force per unit mass of iron equal to one tenth the weight of the iron (0.1g) for saturated iron and for an unsaturated iron sphere. Based on a dipole simulation of a 1.0 T imaging magnet. Lines of constant magnetic field strength are shown.

IV PROTECTING MAGNETIC FIELD HOMOGENEITY

Motion of nearby ferromagnetic objects can change the homogeneity of the magnetic field within an air-core magnet system. These changes have been estimated by IGC, (Guilderland, NY) and Figure IV-1 shows the allowable distance of closest approach of various objects that can introduce 1 or 10 ppm inhomogeneity in the main field of 0.5 and 1.5 T magnets. It can be seen that a 1 kg object such as a wrench can cause a 10 ppm inhomogeneity when placed approximately 2 meters from the center of an 0.5 T magnet. Other examples of inhomogeneities and field shifts due to adjacent steel have been given (20). In the case of a self-shielded magnet or a magnetically shielded room, ferromagnetic objects outside the shield have less effect on homogeneity even at the same level of fringe field (eg, 0.5 mT).

A similar, quantitative nomogram for larger, stationary metal objects is not readily available. The mass of static metal placed asymmetrically is usually limited by the strength of available shim coils and the size of allowable passive shimming in the bore and outside the magnet cryostat. Shim capabilities of two common magnets have been given (8). Most manufacturers give estimates of minimum allowable distances for various ferromagnetic objects, as in Table IV-1, taken with permission from (21). Most of those estimates are more conservative than necessary for stationary objects, as passive shimming techniques have improved rapidly. See Section VI for further information. As pointed out in (8), the influence of ferromagnetic objects on the stability or homogeneity of the magnetic field in the magnet bore is a consequence of the degree of magnetization of these objects. At higher fields, these objects approach magnetic saturation and their magnetization does not increase linearly with magnetic field strength. Therefore, the relative influence on the field in the magnet bore (expressed in ppm) decreases with increasing field strength. Thus, approximately the same minimum distances apply for magnets of different field strengths. Magnetometer mapping of the site for verification of ambient magnetic field stability has been suggested (21) and a limit of 3.5 mT for ambient 50-60 Hz magnetic field oscillations has been given (22).

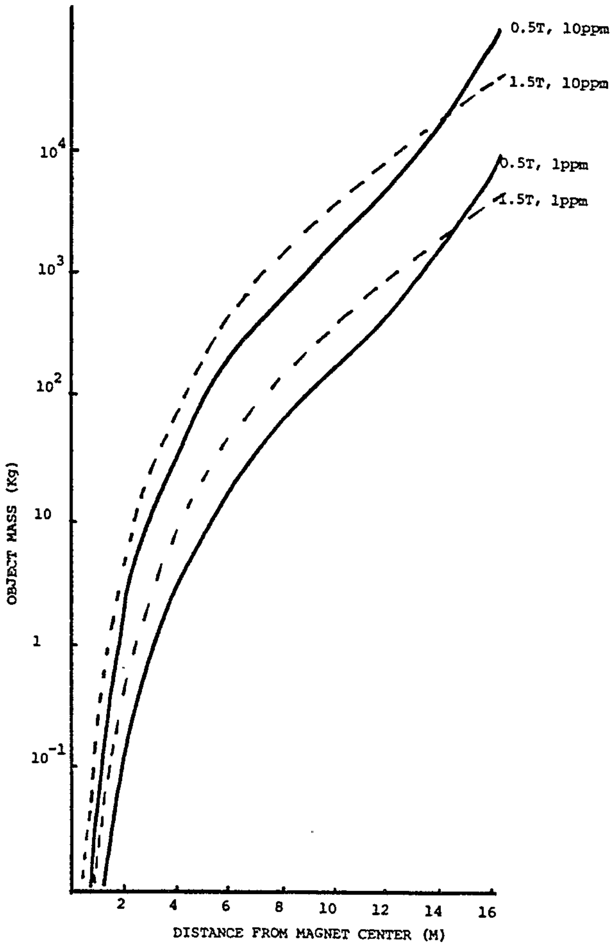


Figure IV-1 Mass of moving magnetic object vs. allowable distance, of closett approach for 0.5 T and 1.5 T air-core magnets (IGC, Guilderland, NY).

TABLE IV-1

PROTECTING MAGNETIC FIELD HOMOGENEITY

DISTANCE FROM CENTER OF MAGNET

> 1 m- STEEL REINFORCEMENT IN FLOOR 3 LBS./SQ. FT.
> 6 m- STEEL GIRDERS, HIGHLY REINFORCED COLUMNS, A/C CHILLERS
> 8 m- WHEEL CHAIRS, STRETCHERS
> 10 m- POWER LINES, TRANSFORMERS
> 12 m- AUTOMOBILES, DUMBWAITERS, ELECTRIC TRANSPORT CARTS
> 15 m- ELEVATORS, TRUCKS
> 30 m- ELECTRIC RAILWAYS

V EFFECTS OF MAGNETIC FIELDS ON OTHER HOSPITAL EQUIPMENT

A. General Considerations

Potentially adverse effects on the operation of many devices are observed with fringe magnetic fields above a certain level which depends on the particular device. For example, devices which depend on the precise positioning of relatively slow-moving electron beams (eg, a color TV set) may suffer noticeable effects at relatively low field strengths. Most medical and consumer devices function well in the earth's magnetic field (ie, ~0.05 mT), but documentation on the effects of stronger magnetic fields on various devices as a function of magnetic induction or field strength is somewhat limited. In available site planning guides, known or estimated magnetic field thresholds are often listed for potentially significant effects on various devices. The thresholds which have been quoted (13 and 23-29) and our current best estimates are summarized in Table V-1. As can be seen, recommendations do not exist for many devices and there are often considerable variations in recommended thresholds. Although little information is given on the severity of effects, it is often possible to exceed these thresholds to reduce facility costs or increase operational efficiency. In relation to Table V-1 it is worth noting that devices such as color and black and white TV systems and magnetic storage media and computer systems are particularly important because they are intimately involved with the operation of an MR system and are often close to the magnet for efficient operation.

Video display terminals are of general concern because they are becoming common throughout a medical facility. Computer electronics are not affected by the lowest fields, but computer system locations are somewhat limited because of the accompanying magnetic storage media. To erase magnetic information completely, such as that on credit cards or magnetic tapes requires a relatively high static field. Thresholds as high as 20 mT have been reported (34).

Since the output of a photomultiplier tube (PMT) is affected by the magnitude and orientation of magnetic fields, a device whose operation is extremely sensitive to PMT gain (eg, a scintillation camera or a CT scanner) can be among those affected by the lowest magnetic fields (31, 32). The entire device or individual PMT's can be magnetically shielded (33) but the large aperture of a scintillation camera will make magnetic shielding difficult in most cases. It is not broadly known to what extent magnetic shielding is already done by various manufacturers of existing equipment.

TABLE V-1

MAXIMUM MAGNETIC FIELD (in mT) FOR ACCEPTABLE OPERATION OF SENSITIVE DEVICES

Device	Information Source (See Reference List)								Recommended (Best Estimate) Maximum Field
	23	24	25	26	27	28	13	29	
1) Scintillation Camera	0.1	0.1	0.1	0.15	-	0.1	0.05	0.2	0.1
2) Rotating ECAT	0.06	-	0.06	-	-	-	-	-	0.06
3) CT Scanner Utilizing PMT's	0.2	0.1	-	0.15		0.1	0.05	0.2	0.1
4) CT Scanner Non PMT	-	-	-	-	-	0.1	-	-	0.5
5) Shielded PMT's	1	1	-	-	-	-	-	-	1
6) Cyclotron	0.1	-	0.1	-	-	-	-	-	0.1
7) Image Intensifier	0.1	0.1	0.1	-	-	0.1	0.05	0.2	0.1
8) Electron Microscope	0.1	-	-	-	-	-	.001	-	0.1
9) LINAC	-	-	-	-	-	-	-	0.1	0.1
10) Ultrasound	0.3	-	-	-	-	-	-	-	0.3
11) Analytical Balance	-	-	-	-	-	-	-	-	0.2
12) Color TV	0.15	-	-	-	-	-	-	-	0.1
13) EEG	-	-	-	-	-	-	-	-	0.1*
14) Mass Spect	0.1	-	-	-	-	-	-	-	0.1
15) Unshielded Video Hard Copy Camera	0.3	1	1	0.2	-	1	-	0.5	0.3
16) Steel Cased Video Hard Copy Camera	1	1	-	-	-	-	-	-	1

TABLE V-1
(continued)

Device	Information Source (See Reference List)								Recommended (Best Estimate) Maximum Field
	23	24	25	26	27	28	13	29	
17) B&W Monitor-Non-Critical	2	-	-	-	-	-	-	-	1.5
18) Cardiac Pace-Maker	1.5	0.5	0.3	1	0.5	0.5	0.5	1.5	1.5
19) ECG	-	-	-	-	-	-	-	-	-*
20) Neuro-Stimulator	-	-	-	-	-	-	-	-	0.5
21) Mechanical Watches	1	-		1	-	3	-	1.5	1
22) High Density Magnetic Storage	1	1	1	0.5	-	1	0.5	1.5	20 (ref 34)
23) Magnetic Credit Cards	20	2	-	1	-	3	-	1.5	20
24) Disc & Tape Drives	-	-	-	-	-	1	-	1.5	1
25) Computers	1	-	-	0.5	-	1	-	-	1
26) X-ray Tube	1	-	-	-	-	-	-	-	1
27) Hearing Aids	-	-	-	1	-	-	-	-	1
28) Electric Motors	-	-	-	1	-	3	-	-	2
29) Photographic Equipment	-	-	-	-	-	3	-	-	2

* More sensitive to changing field (gradient fields) than to B_0.

Electroencephalographs and electrocardiographs may be relatively common in areas near prospective MR imaging sites, the former being extremely sensitive to oscillating magnetic fields and the latter being relatively insensitive. However, quantitative data is limited at this time.

B. Experimental Examples

A more detailed analysis of effects on two types of multi-image cameras and a portable image intensifier (Philips 8V20) is presented below (23). One multi-imager was a floor model with 1/16 inch thick steel casing and the other a compact multi-imager with an aluminum case. These instruments were placed in a Helmoltz coil electromagnet pair of 1.4 meter diameter capable of producing fields ranging up to 2 mT to an axial radius of 60 cm (72% of inside volume). In all cases the equipment was oriented parallel and perpendicular to the magnetic field and images recorded at applied fields between 0 and 2 mT. For the multi-image cameras, a video pattern generator was employed to display an 11 x 15 grid of dots on the internal CRT. The image intensifier study utilized x-ray images of 2 plates of steel with an etched Cartesian square grid on the surfaces between them. A complete description of image distortion would be provided by the deformation or strain tensor. However, compared with translation, rotation or scale change, anisotropy measures image distortion which is most likely to cause errors in measurements and may be most difficult to correct.

A simple measure of global or maximum anisotropy in the image was defined as the maximum discrepancy of length changes between any two line segments of lengths equal to at least 35% of the image height or width and lying in any position and orientation within the image (23). In practice this was measured as in Figure V-1 using the lengths, L_i, of the lines between: 1) 8 reference points on the image periphery; 2) the bisector of those lines and the center point; 3) the 8 reference points and the center point. The peripheral reference points were chosen to encompass approximately 80% of the height and width of the field of view. The ratio of the line length L_i with magnetic field on and off is R_i. Anisotropy, A, is then the ratio of the maximum measured field-on to field-off ratio and the minimum ratio:

$$A = \frac{R_{max}}{R_{min}} \qquad (1)$$

Anisotropy usually increased essentially linearly with magnetic field strength up to at least 1.8 mT. As shown in Table V-2, the maximum rate of change in anisotropy over the 1.8 mT range was 2.2%/mT for the aluminum framed compact multi-imager and 1.9%/mT for the steel cased multi-imager. The steel-cased imager did show hysteresis (induced magnetization) which could provide problems with resistive MR systems where the magnetic field is turned on and off regularly. Image translation and rotation are reported in Table V-3.

There appears to be no threshold magnetic field for distortions in CRT-type devices. Criteria can be chosen from the information on effects provided, but some typical benchmark field strengths might be as summarized in Table V-4. A 4% anisotropy corresponds to somewhat less than the 2% nonlinearity often defined as the limit for precision measurements in ultrasound and computed tomography. This occurred at 0.3 mT in an unshielded TV monitor and 0.1 mT in the image intensifier. On the unshielded monitor and image intensifier, strong, 10% anisotropy begins at 0.5 mT and 0.2 mT, respectively. Annoying translation or rotation begins at 1.3 mT on the black and white monitor and severe resolution loss at 0.3 mT on the image intensifier.

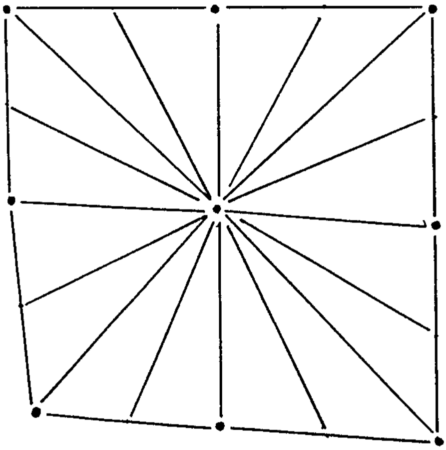


Figure V-1 Line segments for image anisotropy and other distortion measures. These lines are drawn between the measured reference points in the images (large dots) and between the central reference point and the bisectors of the lines between the peripheral reference points.

TABLE V-2
MAGNETIC-FIELD-INDUCED ANISOTROPY IN MULTI-IMAGE CAMERAS AND PORTABLE FLUOROSCOPES

	ANISOTROPY (% per mT)		
	Horiz	Vert	Axial
Compact Multi-imager	14-22	-	-
Multi-imager steel cabinet	1.5-1.7	1.4-1.9	-
Image intensifier	22	-	45

TABLE V-3

MAGNETIC-FIELD-INDUCED TRANSLATION AND ROTATION

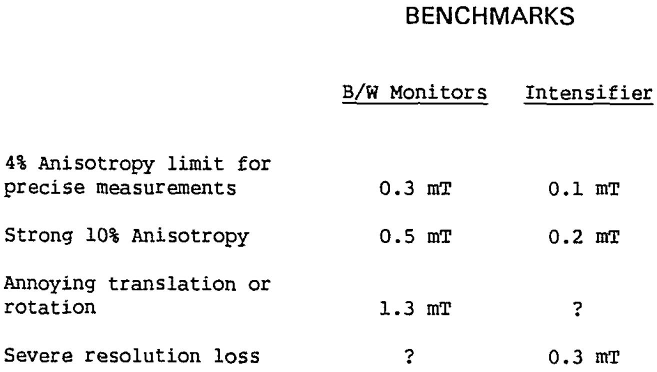
	Translation				Rotation	
	Horiz.		Vert.		Axial	
	Max %*	%/mT	Max %*	%/mT	Max DEG	DEG/mT
Compact Multi-imager	14	14	-	-	8	5
Multi-imager steel cabinet	4	-	8	4	-	-
Image intensifier	14	14	-	-	-	-

*** Maximum translation in % of full field length or height over 0-2mT; 0-1 mT for image intensifier.**

TABLE V-4

MAGNETIC FIELDS FOR SIGNIFICANT IMAGE DEGRADATION

In unshielded image intensifiers and monitors there appears to be no threshold magnetic field for distortions.



	BENCHMARKS	
	B/W Monitors	Intensifier
4% Anisotropy limit for precise measurements	0.3 mT	0.1 mT
Strong 10% Anisotropy	0.5 mT	0.2 mT
Annoying translation or rotation	1.3 mT	?
Severe resolution loss	?	0.3 mT

VI STATUS OF MAGNETIC SHIELDING

A. Introduction

The field outside the magnet bore may cover an extremely large volume. The field extends in all directions and frequently goes beyond the boundary of the MR imaging room. This area is referred to as the fringe field region, and, in the absence of magnetic shielding, fringe fields are proportional to the strength of the magnet. Table VI-1 illustrates the approximate maximum field extent of the 0.5 mT fringe field of magnets of different strengths.

TABLE VI-1
MAXIMUM DISTANCE FROM MAGNET CENTER
YIELDING 0.5 mT FRINGE FIELD

Distance in:	0.15T	0.3T	0.5 T	1.5 T
meters	6.1	7.6	9.0	12.8
feet	20	25	29	42

An extended fringe field region is undesirable in a hospital environment because of its influence on and interference with other hospital equipment. Consequently, a detailed knowledge of a magnet’s fringe field and its relationship to surrounding equipment and activities is an essential part of any site planning and installation program.

The most common method employed to date to limit the extent of the fringe field is the construction of high flux return paths with sheets of ferrous alloys to confine or alter the shape of the fringe fields. This solution is not without complications because the use of large amounts of iron for shielding affects the forces on the magnet coil and the uniformity of the field within the bore of the magnet. In addition, in some partially shielded configurations, edge effects along the periphery of the shielding may result in field strengths in excess of those present without shielding.

At least three possible approaches to the magnetic field screening can be identified (8).

1. Closed flux path screens with iron alloys.
2. Partial screening with iron alloys.
3. Active shields using equivalent current shells.

One example of an active shield at the entrance to an MR Imager room has been presented (35). Active shields have not been used extensively to date and will not be discussed further.

B. Choice of Magnet Screens

When an adjacent area has been identified in which the fringe field is unacceptably high, one may choose from various passive shielding methods.

1. A screen which shields the local zone by enclosing the zone itself in a closed-flux path (eg, an iron box around the computer).

2. A closed-flux path screen around the magnet which can be either within the magnet housing (so-called selfshielding magnets) or around the magnet so that most of the magnetic field energy is confined within the outside boundary of the box.

3. Partial or discontinuous high-flux screens which are positioned to cause local distortions of the field sufficient to accommodate adjacent areas (eg, a distortion just large enough to accommodate a CT scanner).

Generally a closed-flux path shield will be more efficient at screening than partial screening, such as a single iron sheet placed between the magnet and the zone to be shielded. With proper design, the closed shield can save cost and space by serving also as an RF shield (36).

The general criterion for shielding is to use as little iron as possible because of cost and effect on magnet homogeneity.

C. Rules-of-Thumb For Closed-Flux Shields

Assuming a spherical screen rather than a box, the following equation can be used to relate the (source) field outside the screen (H_{out}) to the field inside the screen (H_{in}):

$$H_{in} = (2d/\mu t)\ H_{out} \qquad (2)$$

The screen thickness is t and diameter is d. The permeability of the screen material, m, is assumed to be independent of H (8). In most cases the screen material is only partially saturated, so that these equations overestimate the field reduction.

For more extensive shielding, it is generally better to consider shielding the entire magnet. An estimate for the thickness of the iron (d_2-d_1) needed to reduce the field by a factor of f can be obtained from the following equation:

$$f = \{1 + 2/9\ [1-(d_1/d_2)^3]\ (\mu-1)[1-(1/\mu)]\} \qquad (3)$$

where d_2 and d_1 are the average inner and outer diameters of the screen of permeability m (8).

These equations are generally not adequate for specific installations which must include both screening and structural iron and and their effects on homogeneity. It is also true with closed-flux path shields, that the mass of the screen remains approximately constant for a given field reduction and magnet strength regardless of the shield’s average distance from the magnet. In addition the effects of partial screens are not easily calculated. For partial screening situations a handbook giving screening values for various isolated, finite plates of different thicknesses and locations relative to the magnet center ray is available (Fig. VI-1) (8). Even though high-permeability materials are very efficient shields, in many cases the real concern is the maximum flux density that can be obtained in a material. This may be satisfied in many cases with steel, thus minimizing cost.

D. Configurations Used In Existing Sites

Magnetic field shielding and site planning is becoming more complex as magnet field strengths increase. In many sites, installation of magnets greater than 0.5 T would be impossible without some sort of shielding. Most manufacturers can now provide reference sites for various styles of shielding.

E. Self-Shielding Designs

Siemens and Oxford offer self-shielding options which are installed as part of the magnet housing. The Siemens option provides the approximate field reduction factors shown in Table VI-2 for areas 3 meters or more beyond the magnet (37).

TABLE VI-2

SELF-SHIELDING FIELD REDUCTION FACTORS

Field Strength	Field Reduction Factor	Weight
0.5T	5	21,000kg
1.0T	4.5	21,000kg
1.5T	2.8	21,000kg
1.5T	7.5	31,000kg

F. Discrete Steel Plate Shielding

Opposed pairs of steel plates have been used in the walls surrounding systems by Philips Medical Systems and others to reduce the fields outside the magnet room. As illustrated in Figure VI-1, increased steel thickness will reduce the magnitude of the fringe field lines (24). The use of such steel plates will disrupt, to some extent, the homogeneity of the central imaging volume. However, by using symmetrical plates, the effect on homogeneity is significantly reduced (38, 39).

A variation on the use of large discrete plates has been utilized by Philips Medical Systems. This variation is referred to as a magnetic dome. In this method a dome is constructed from relatively small modular sheets with intervening spaces for aesthetic reasons and to reduce construction costs in existing facilities.

G. Closed-Flux Shield

Many installations have been completed which use closed-flux path shielding. Diasonics recommends an enclosing steel box resting on a copper floor to accomplish RF as well as fringe field shielding. This approach seems cost effective, because only the inside or outside layer of steel requires welding or other electrical connection for the RF shielding. An interesting variation between the discrete plate geometry and the closed-flux shield design has been installed at the Henry Ford Hospital in Detroit, Michigan, where a continuous steel cylinder is used to enclose the magnet (40).

H. Magnetic Shielding Software

Most manufacturers now possess special purpose computer programmes which can analyze fringe fields in three dimensions and can be used to design both closed-flux shields and discrete plate shields to meet the varying requirements of individual customers. A complete three dimensional field calculation program can be obtained at considerable expense from (41). For geometries which can be simulated adequately by a 2-dimensional arrangement, a Fortran program is available in the public domain (42).

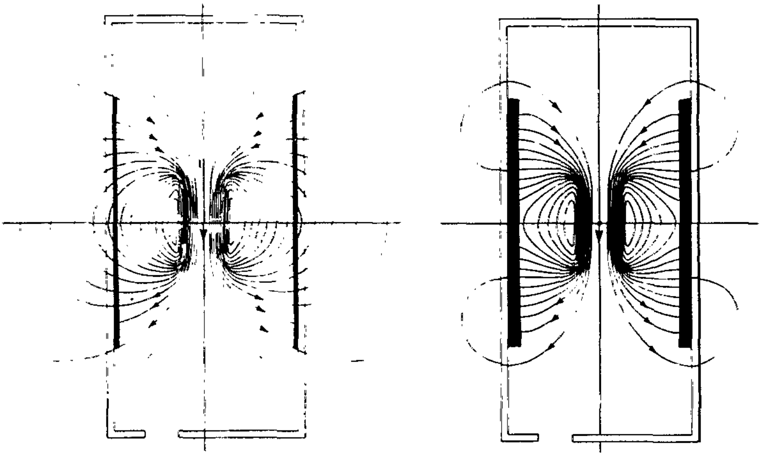


Figure VI-1 Increased shielding plate thickness improves shielding (24).

VII RADIOFREQUENCY SHIELDING*

Figure VII-1 shows the interference coupling paths that are present between various sources of noise and the MR detection coil. In pathway A, radiative noise from fluorescent lights, capacitors, and power supplies is produced which can result in artifacts. In pathway B, a conducted current or voltage will emit a magnetic field which can be detected by the MR coil. Electrical lines, heat sensory devices, and sprinkling systems required by building codes enter the magnet room and will be a source of radiative noise unless decoupled. In C, conduits entering the scan room can couple noise that has been induced outside the magnet room to the coil. By far the greatest sources of noise are the lines (D) that are directly connected to the magnet from the computer, the RF power supply, and gradient power supplies.

The frequency spectrum spanning the clinical MR imaging frequency range is presented in Figure VII-2. At the bottom of this figure, the magnetic field strengths of 0.1 to 1.5 T are presented with their corresponding frequencies. Although this portion of the electromagnetic spectrum is very heavily populated, most MR units can be easily adjusted to avoid a specific RF frequency. In Figure VII-3, the results of an ambient environmental RF survey of one planned facility are presented. A loop antenna using a calibrated receiver was tuned to 6.25 and 25.5 MHz and positioned in the four directions indicated. Peak power levels were found not to exceed 80 dB Re 1 µV/m Another example of field survey equipment is given in (20).

Manufacturer’s specifications for shielded rooms vary from 60 dB isolation to 120 dB, the latter being a conservative figure, utilized for spectroscopic applications. Since it is relatively easy to attain 80 to 100 dB isolation without significantly increased cost over lower isolation, most manufacturers specify 80 to 100 dB isolation (43). For example, Siemens specifies for their 21 MHz (0.5 T) system -- 80 dB isolation at 2 MHz, 100 dB at 5 MHz and 110 dB from 30-100 MHz (21). Shielding requirements do depend on the ambient electromagnetic noise in the area and a few MR system suppliers specify ambient electric and magnetic field strengths which will allow prior system operation with the specified RF shielding or system properties alone. One company has established quantitative electrical field specifications of 100 mV/m for acceptable ambient RF prior to RF shielding for their 1.5 T system (22).

* Adapted with permission from (16).

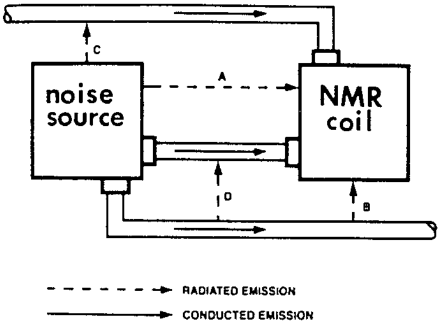


Figure VII-1 **Interference coupling paths between the MR coil and the sources of noise.**

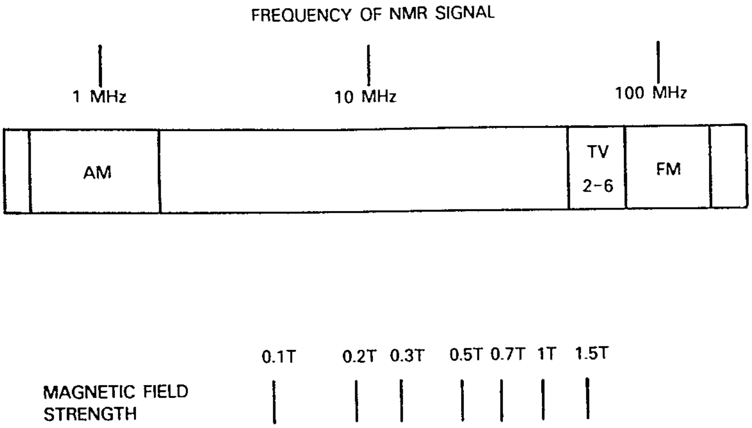


Figure VII-2 **Frequency range and corresponding magnetic field strengths for MR imaging.**

ENVIRONMENTAL RF

(Corrected dB)	ANTENNA POSITION			
	E-W	NW-SE	N-S	NE-SW
LOOP ANTENNA 6.25 MHz				
Peak	80	72	80	80
Average	32	37	37	38
LOOP ANTENNA 25.5 MHz				
Peak	47	56	62	58
Average	21	23	36	36
LOOP ANTENNA 25.8 MHz				
Peak	41	54	74	70
Average	26	31	38	42

Figure VII-3 The environmental measurements of ambient RF levels indicated a maximum of 80 dB re 1µV/m.

Without a Faraday cage 100 dB is difficult to achieve in practice since any construction other than a solid shield allows for RF leakage. RF shielded enclosures are sold by numerous companies specializing in this field. An example is shown in Figure VII-4 (44). Information on various manufacturers of shielded enclosures may be obtained from an MR Site Planning Consultant or from manufacturers of MR systems. A typical shielded enclosure costs $50,000 to $110,000 installed. A physicist or other hospital representative should verify the performance of the RF enclosure with the supplier after the enclosure is installed, before any MR imaging equipment installation begins.

All users and vendors of MR imaging systems agree that radiofrequency shielding is necessary. However, disagreement exists as to the type and extent of RF protection required. Radiative interference from ambient RF is thought to be of minimal concern in comparison to the noise conducted by the lines leading

into the MR unit. Thus some vendors feel that magnets could be shielded locally through the use of zinc (or other material) coating the inside of the fiberglass housing. The opening of the magnet bore provides a waveguide effect for incident RF. The effectiveness of the bore opening as an attenuator decreases as the magnetic field strength increases since shorter wavelengths easily pass through to the RF coil. MR imagers operating at 0.15 T have much lower signal-to-noise ratio than those operating at 1.0 T and greater. Thus noise reduction will result in more apparent improvement with lower field systems.

Several manufacturers have designed self-shielding MR imaging systems, extending tubes from each end of the magnet, with or without end caps. The extended tubes and the end caps tend to increase the small number of claustrophobic reactions in patients. RF shielding can be incorporated into magnetic field shielding and this approach is being pursued by some MR system manufacturers.

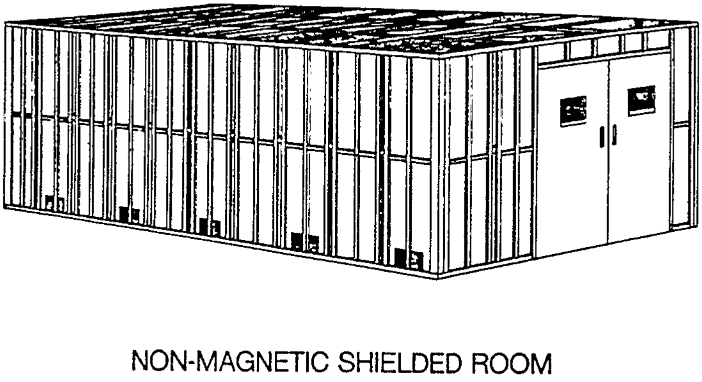


Figure VII-4 A Faraday cage can provide greater than 100 dB attenuation.

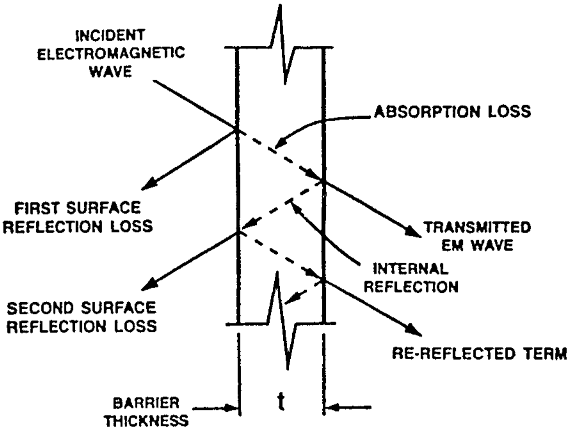


Figure VII-5 Losses due to a solid ‘conductive barrier.

Shielding Effectiveness = Reflective Losses + Absorption Losses + Re-Reflective Losses

REFLECTIVE LOSSES $= 20 \log \frac{Z_{Wave}}{4Z_{Barrier}}$

ABSORPTION LOSSES $= 8.686\ \alpha t$

RE-REFLECTIVE LOSSES $= 20 \log \left(1-e^{-2\sqrt{2}(t/\delta)}\right)$

Figure VII-6 The SE (attenuation) of a barrier depends upon absorptive, reflective, and re-reflective losses. (Symbols are defined in the text.)

At the Cleveland Clinic, RF shielding was installed with the hospital physicist acting as a general contractor and designer. The following discussion results from that experience and is reprinted with permission from (45).

The opportunity presented itself to have RF shielding hidden during construction of the facility. An attenuation or shielding effectiveness (SE) of 90 dB was specified after consultation with subcontractors. As shown in Figures VII-5 and 6 the SE is the result of the combined effects of reflective and absorption losses. For reflective losses, Z_{wave} is the electromagnetic wave impedance while $Z_{barrier}$ is the intrinsic impedance of the barrier. The wave impedance is the ratio of the E to the H field, while the barrier impedance depends highly upon the properties of the material chosen. Primarily it is a function of the relative conductivity (s) of the material, which changes with the frequency of the incident radiation (46). Absorption losses depend upon α, the absorption coefficient of the material chosen and the thickness of the absorbing material. Re-reflective losses vary exponentially as a function of the thickness of the absorbing material and skin thickness (1/ d).

The composite shielding attenuation for copper foil and sheet is given in Figure VII-7, where SE is plotted versus incident frequency between 1 and 100 MHz.

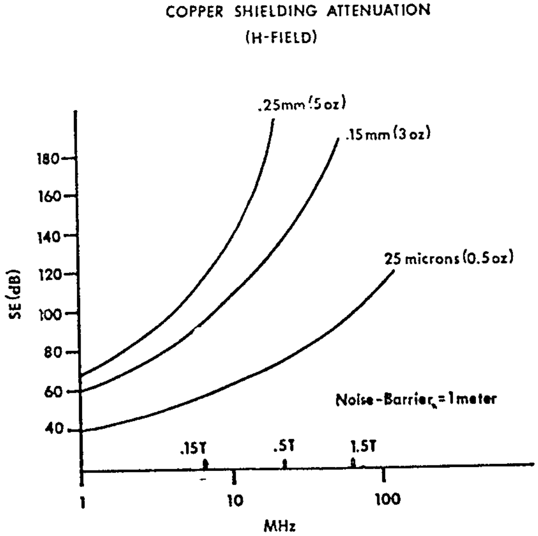


Figure VII-7 Attenuation (SE) for solid copper in the range of frequencies encountered with MR imaging.

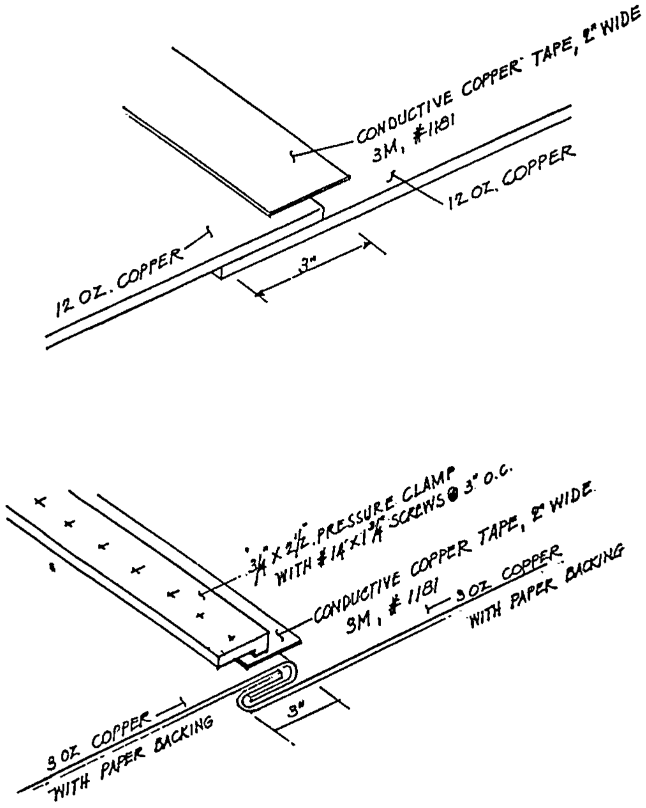


Figure VII-8 Typical construction methods for high integrity seams necessary to maintain a high SE. Positive pressure (screws or nails) should be used (47).

At a source-to-barrier distance of 1 meter, even 25 microns of Cu provides a good degree of shielding and thicknesses of 3 and 5 oz Cu exceed 90 dB. Solid Cu sheets can be soldered together to provide the best barrier integrity. Soldering is only possible on horizontal surfaces, however, and tape, staples, or reinforcing bars must be used on vertical surfaces (Figure VII-8). Twelve oz Cu was used below grade, since mechanical strength and integrity were important during concrete pouring. Wall construction methods allowed 3 oz paperback foil to be used.

RF leakage through an aperture is dependent upon the longest dimension of the aperture and the wavelength (x) of the RF. When l is less than twice the longest aperture dimension, the electromagnetic energy will pass freely through the opening without being attenuated. For wavelengths equal to twice the opening (l =2D) the shielding is 0. When l is greater than twice the maximum dimension of the aperture, attenuation occurs, due to an increase in the barrier impedance. In Figure VII-9 shielding losses for various aperture sizes in Cu are given. For holes that are <250 µm (0.01”), little reduction in attenuation occurs. However, the effect of having a multitude of these tiny holes will greatly amplify RF penetration. Thus, each of the holes from staples and nails was covered with copper tape.

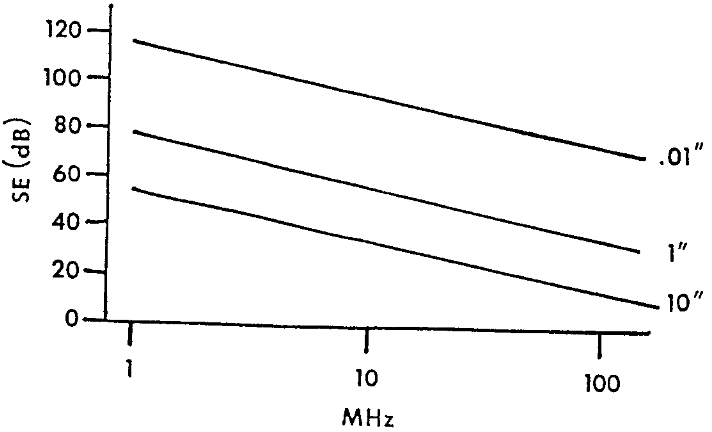


Figure VII-9 Shielding loss due to various sized apertures in barrier. Multiple small holes (0.01 in.) diameter can have an effect on overall barrier integrity. Large diameter apertures will permit the ready transmission of the incident RF.

The compromise of the RF barrier due to penetration by conduits, pipes, and ventilation ducts was addressed through the use of waveguides. The waveguide shown in Figure VII-10 also serves to decouple conductive noise along the conduit. A PVC insert breaks the pipe continuity while copper tape is wrapped around the plastic insert. The overlap of the tape on the plastic exceeds 5x the gap between the tape and the conduit. An acceptable level of SE is possible with this technique when the conduit is up to a few inches in diameter, but RF waveguide assemblies (Figure VII-11) are best for large openings. The honeycomb pattern provides individual waveguides whose number and length-width ratio control the degree of RF attenuation. In Figure VII-12, the waveguide attenuation for a honeycomb assembly that was inserted in a 61 cm (24”) ventilation pipe is given. The panel is a square that is 61 x 61 cm (24” x 24”) with approximately 16,000 holes. These waveguides will accumulate dust, since all room air must pass through the vent and clean-out traps for access are necessary.

Since the patient is fairly isolated during an MR examination, it was felt that direct viewing and verbal communication should be possible.

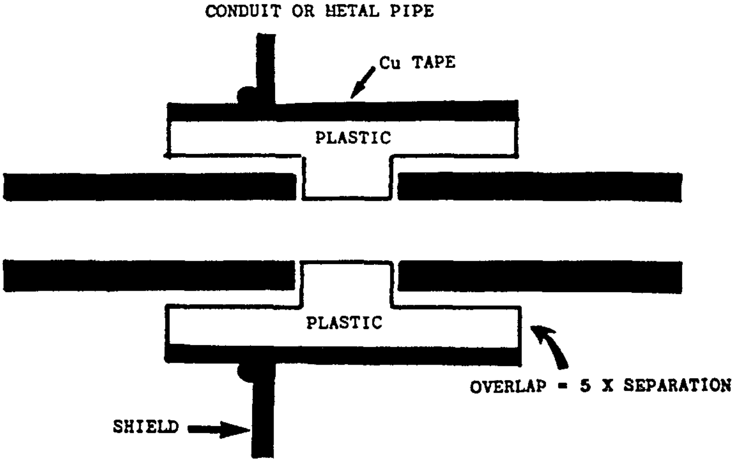


Figure VIB-10

A simple waveguide technique protects apertures from RF penetration. The waveguide is used in conjunction with plastic decoupling of the conduit to eliminate noise. The copper tape must be carefully applied to ensure it does not touch the conduit. It is usually necessary to isolate the RF shield from entering pipes so that the shield is grounded only in one location.

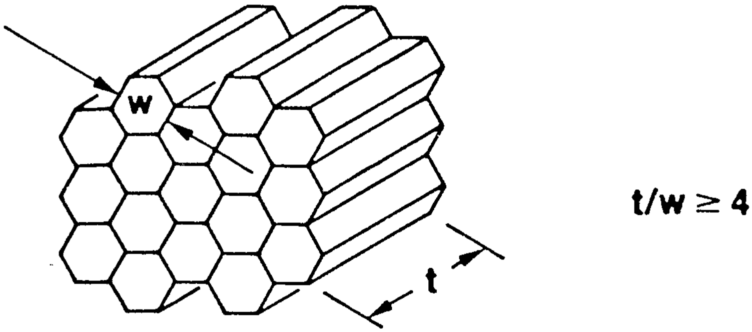


Figure VII-11 For large openings (eg, ventilation ducts) a commercially available honeycomb waveguide assembly may be necessary.

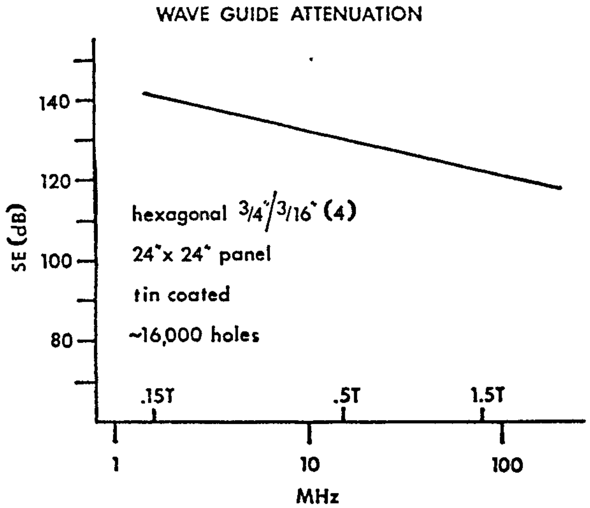


Figure VII-12 The RF attenuation for the waveguide given in this figure is in excess of 100 dB at 100 MHz.

The patient viewing window was constructed of bronze mesh. Testing was carried out using a single layer of copper mesh (24 x 24 x 0.014”), or 61 x 61 x 0.036 cm. This mesh provided only 70 dB attenuation at 60 MHz and was felt to. be insufficient even though its optical properties were superior to what was finally chosen.

The final barrier was constructed using 279 μm (0.011”thick) bronze screen of 5.5 x 5.5 strands/cm (14 x 14 strands per inch). Two layers of this mesh were chosen which provided 100 dB shielding at 60 MHz for the very large viewing area which was designed (45). The viewing area also provided the return for the room air conditioning and was constructed of panels which are removable to allow magnet entry and exit.

The magnet room was equipped with an RF shielded door (17). The door locking mechanism provided for positive closure at 3 positions as well as double metal contact around the door edge. The door was commercially available and provided greater than 100 dB shielding. To provide easy entrance and exit, a brass floor plate with a low slope was installed. The MR frequency spectrum measured with no sample in the coil showed white noise and the mean noise value increased marginally when the doors of the magnet room were left open.

The greatest interference detected was from conducted noise originating with the computer and associated electronics. The twisted pair technique (Figure VII-13) was used to reduce this noise. This technique uses the return pathway with a differential amplifier to eliminate conductive noise. Spurious noise induced in the wire will be eliminated. Further, radiative noise produced by the wire is decreased, since noise induced in the other wire of the pair can be eliminated.

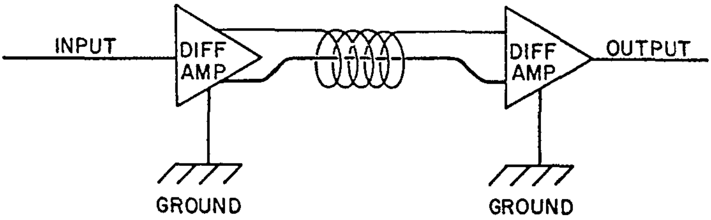


Figure VII-13 By providing a return signal path, the twisted pair technique uses a differential amplifier to eliminate both radiative and induced noise in the lines.

VIII CHECKLIST

The following lists summarize most topics to be considered in designing an MR imaging facility. The list of functional areas can be used as the basis for estimating the area necessary once the functional requirements of a particular site are known.

A. Functional Areas

The first group is normally required for an MR imaging facility:

i) Scan Room
   Control Room
   Computer Equipment Room (include RF equipment and power supplies)
   Reading Room (include physician's console)
   Cryogen Storage

The second group is required adjacent to the MR imaging facility but some areas can be shared with other imaging services when necessary or when joint space can be designed properly.

ii) Film Processing
   Quality Control and Service
   Patient Preparation, Recovery and Emergency Procedure Area
   Patient Reception and Waiting Area
   Stretcher Holding Area
   Storage (supplies, magtapes, film, etc)
   Washrooms
   Soiled Utility
   Clean Utility

The third group lists additional functions, likely to be required, which can be both remote from the MR imager and shared with other services in extenuating circumstances.

iii) Secretarial and Transcription Services
   Conference Area
   Additional Storage (film library, magtapes)
   Offices

B. Construction and Access Considerations

Equipment transportation, unloading and installation access.
Floor loading (including access routes)
Floor levelness
Ceiling heights (especially magnet room and access route)

Access for cryogens.
Cryogen venting (normal and quench)
Controlled access to facility and well-controlled access to magnet room

C. Protecting Magnetic Field Homogeneity

Location and amount of steel shielding
Other structural iron and steel
Large ferrous structures or objects
Symmetrical location of ferrous structures
Moving ferrous objects (eg, elevators, lift trucks and vehicular traffic within and outside the building)

D. Protecting Surrounding Environment from Magnetic Fields

A three-dimensional survey of magnetically sensitive devices and equipment should be undertaken. Tolerable distances from the center of the magnet will depend on magnet field strength and shielding design. Use the field strengths in Section V as a guide.

E. Radiofrequency Shielding

Design appropriate RF shielding based on a site survey according to the manufacturer's specifications. Avoid light dimmers and fluorescent lighting ballasts within the magnet room.

F. Facility Environment

Electrical supplies
  - **voltages, current and phases**

Air conditioning
  - **general area, computer room (temperature, humidity and filtration)**

Water supply and floor drains
  - **include sink for phantom filling and draining**

Chilled water supply
  - **temperature, flow rate and tolerable temperature fluctuation**

Personnel protection
  - **establish controlled areas and metal detection routines**

Fire Detection and Safety
  - **no sprinklers; non-ferrous extinguishers**

Telephone Service
  - **separate lines for operator, physician and service personnel (near computer)**

Housekeeping
  - **no ferrous cleaning tools or supplies**

IX ACKNOWLEDGMENTS

The authors gratefully acknowledge the cooperation of the many individuals, companies, and other organizations who have given permission to use their illustrations and other information. The mention (or not) of a specific manufacturer is not intended as a recommendation or endorsement. The reader is advised to consider a much broader range of factors in selecting an MR imager supplier than is discussed in this report.

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