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Electric and Magnetic Fields in a Magnetic Resonance Imaging Facility: Measurements and Exposure Assessment Procedures

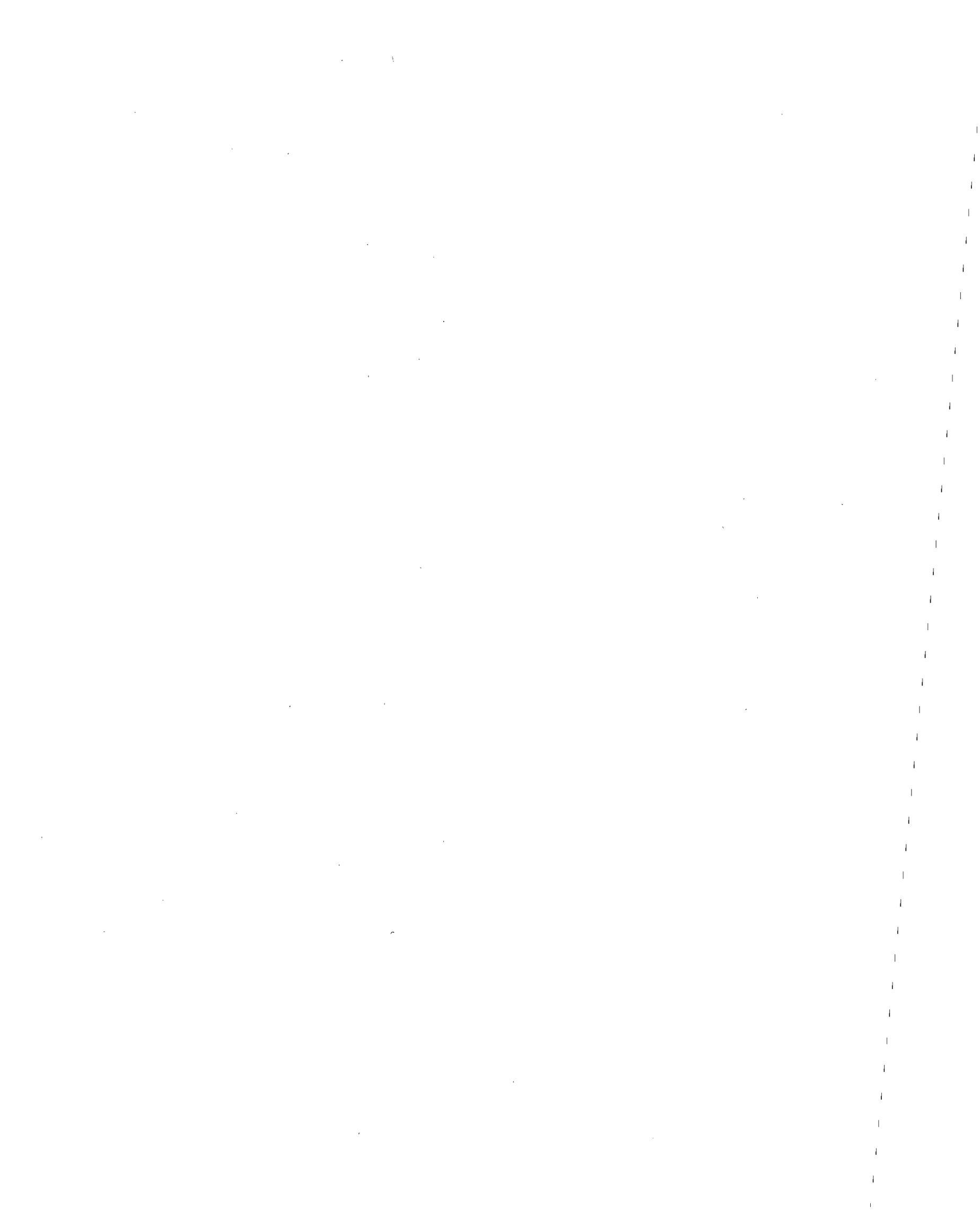
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Prepared by

T. Dan Bracken, Ph.D.
T. Dan Bracken, Inc.
5415 SE Milwaukie Ave. #4
Portland, OR 97202

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18. Abstract (Limit: 200 words) A pilot study was conducted to test protocols for assessing exposure to magnetic and electric fields among workers at magnetic resonance imaging (MRI) facilities. Static magnetic fields, pulsed gradient fields, pulsed radiofrequency electric and magnetic fields, and extremely low frequency, very low frequency, and low frequency magnetic fields were measured in an MRI facility. Data were captured at 5 second intervals over a period sufficient to capture three wave forms at a measurement location. Hall effect sensors were used to measure the static field, and air core induction coils were used to measure the power frequency magnetic fields. At MRI personnel work stations, the measured static fields ranged from 160 millitesla (mT) at the magnet face to 1.5mT at the console, where the operator spends most of his time. The static field measurements in the facility corresponded well with the contours provided by the system manufacturer, confirming that static field exposures can be estimated by combining manufacturers' data with time/motion analysis. The use of a bar code scanning system was evaluated for recording personnel locations in the facility. Time spent near the magnetic face clearly dominates the exposure estimates. The author suggests that additional study be done to compare the time motion estimates of exposure with dosimeter measurements, to characterize gradient fields for different imaging protocols, and to evaluate the use of MRI facility records, such as procedure log books, to estimate exposures.			
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ABSTRACT

A pilot study to test protocols for assessing magnetic field exposures of technicians, nurses and anesthesiologists at magnetic resonance imaging (MRI) facilities was performed. Protocols were developed for measuring static magnetic field (≤ 2.0 T), pulsed gradient fields (≤ 30 kHz), pulsed radio frequency (RF) electric and magnetic fields (10 - 100 MHz) and ELF, VLF and LF (5 Hz - 300 kHz) magnet fields in the MRI facility. The field measurements, except for RF, were made with a personal computer based wave capture system (Multiwave™ System, Electric Research and Management, Inc., State College, PA USA). The system was manually triggered to capture data at five second intervals over a period sufficient to capture three wave forms at a measurement location. For the ELF measurements, a 5 Hz base frequency was employed with 2048 samples per waveform providing frequency content up to about 5000 Hz. The system employed Hall-effect sensors to measure the static field and air-core induction coils to measure the ELF, VLF and LF magnetic fields. Four air-core coils were mounted in a staff at heights of 0.8, 1.1, 1.4, and 1.7 m. The staff was positioned vertically on the floor for measurements in work areas. It was also positioned horizontally along the patient table for several sets of measurements. RF fields were measured with an Isotropic Broadband Meter (Model HI-3002, Holaday Instruments, Eden Prairie, MN USA). A prototype Hall-effect personal static field dosimeter was also tested (Holaday Instruments, Eden Prairie, MN USA). Patients were not present when the protocols were tested at the Oregon Health Sciences MRI Facility, which employs a General Electric Signa Advantage 1.5 T MRI System. Initial evaluation of the instrument performance indicated that electromagnetic interference from the MRI RF fields affected the low frequency measurements (since corrected by the manufacturer). Consequently, lower frequency magnetic field measurements were made with the RF pulses fully attenuated. At MRI personnel work stations the measured static fields ranged from 160 mT at the magnet face to 1.5 mT at the console, where operators spend most of their time. The field pulses used to establish gradients in the imaging volume ranged from 2.0 μ T rms at the magnet to 0.07 μ T rms at the operator's console. These gradient fields exhibited complex wave forms, reflecting the three independent pairs of gradient coils in the magnet bore. The 63.86 MHz RF field at the magnet face was below the 0.001 A²/m² limit of detection for the broadband meter. The static field measurements in the facility corresponded well with the contours provided by the system manufacturer, confirming that static field exposures can be estimated by combining manufacturers' data with time-motion analysis. The use of a bar code scanning system (TimeWand 1, Videx, Inc., Corvallis, OR USA) was evaluated for recording personnel locations in the facility. The time-in-location data from the scanning system was combined with the field contours and gradient field data to estimate exposure for one person participating in the tests. Over a one-hour period while this individual was moving frequently in and out of the MRI magnet room his estimated time-weighted average exposure was 11 mT for the static field and 0.2 μ T rms for the gradient field. Time spent near the magnet face clearly dominates these exposure estimates. More research is recommended to: 1) compare the time-motion estimates of exposure with dosimeter measurements; 2) characterize gradient fields for different imaging protocols; and 3) evaluate the use of MRI facility records, such as procedure log books, to estimate exposures.

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Electric and Magnetic Fields in a Magnetic Resonance Imaging Facility: Measurements and Exposure Assessment Procedures

1.0 Introduction

Magnetic resonance imaging (MRI) is a powerful new technology for producing detailed pictures of body organs and chemicals [Edelman and Hesselink, 1990]. The process is based on the phenomenon of nuclear magnetic resonance (NMR) and takes advantage of recent technological advances in producing large homogeneous magnetic fields and high speed computers. Since MRI's introduction in the mid-1980's, the technology has grown rapidly: there are currently about 10,000 technologists working at 2250 facilities in the United States. Associated with the MRI process are three types of electric and magnetic fields. These are: 1) a static magnetic field of up to 2 T in the bore of the magnet used to align the nuclear spins; 2) low frequency (< 10 kHz) magnetic field pulses used to produce field gradients in the homogeneous static field; and 3) RF (4-170 MHz) electric and magnetic fields pulsed at frequencies less than 10 kHz used to excite the nuclei from one state to another. The magnetic fields found in an MRI facility contribute to a unique occupational environment. In anticipation of a possible epidemiological study on MRI technologists, the National Institute for Occupational Safety and Health (NIOSH) contracted with T. Dan Bracken, Inc. to develop, investigate and evaluate procedures for measuring exposures of MRI technologists to electric and magnetic fields.

The purpose of this report is to describe the results of an evaluation of measurement procedures at the Oregon Health Sciences University (OHSU) MRI facility. These procedures included field measurements, time-activity assessment, and the safety of the exposure assessment personnel. A procedure for solicitation of MRI facilities to participate in an exposure assessment is also presented, along with recommendations for future work in the area of exposure assessment in MRI facilities.

The measurement activities proposed for the evaluation included a complete set of static, low frequency and RF field measurements. Because of the uniqueness of the MRI environment, several measurement questions and assumptions required investigation before a final protocol could be established. Therefore, the number of measurements that were proposed during the evaluation exceeded those that would be incorporated into an exposure assessment protocol. Also, the number of measurements proposed turned out to be an ambitious undertaking for a single day with equipment that had not been tested there previously. Consequently, the number and type of measurements performed

fell short of those that were planned. Nevertheless, the objectives of characterizing the magnetic field environment and evaluating measurement procedures were achieved.

The floor plan of the OHSU MRI facility is shown in Figure 1.1. It consists of an MRI exam room where the large static field superconducting magnet is located, a control room where the computer console is located, a computer room and areas for patient reception, access, recordkeeping, and other activities. The MRI exam room is RF shielded to prevent interference to the MR signals from outside noise sources. Two technologists are usually present when a procedure is performed. They do not both necessarily remain in the control room through the duration of a procedure and do not routinely enter the exam room during an MRI procedure. The OHSU MRI facility is in almost continuous use for patients. Because the measurement procedure evaluation required special operating conditions that would interfere with normal operation, the procedure evaluation was performed during non-clinical hours on Sunday, February 28, 1993.

The MRI procedure relies on a strong uniform static magnetic field over a volume the diameter of the human body. The OHSU MRI facility uses a General Electric Medical Systems Signa Advantage 1.5 T System which employs a superconducting magnetic with a 1.5 T field in its bore. This field remains constant whether MRI imaging is taking place or not.

Radio frequency (RF) pulses at 63.86 MHz are used to resonate with protons that are aligned in the 1.5 T field and create an MR signal of the same frequency. The exact frequency depends precisely on the static field. The short RF pulses (typically 1-20 ms) are applied in a specific sequence depending on the imaging protocol. The pulse sequence repeats after a repetition time (TR) on the order of hundreds or thousands of milliseconds depending on the protocol. The MRI signal is detected at a time, TE (echo time), after the RF pulse. Several RF pulses of slightly different frequencies are contained in one repetition interval.

In order to create spatial variation (gradients) in the static field, gradient field pulses are applied during and after the RF pulses. The spatial variation in the field results in a set of MR signals whose frequencies are dependent on location in the field. Through Fourier analysis of repeated signals it is possible to associate an MR signal with all the locations in the volume under examination. Because the signal is related to the nature of the tissue in which it originates, it is then possible to create a visual image of the tissues in the entire volume.

Thus, within each interval of length (TR) there are a series of RF pulses and gradient field pulses dependent on the particular MR protocol selected. A simplified graphic for the fields applied during a spin-echo imaging sequence are shown in Figure 1.2. The fields associated with these pulses extend beyond

the bore of the static field magnet. The measurements described here characterize the static and time-varying fields in the work areas frequented by MRI technologists, nurses and nurse/anesthesiologists.

Determination of field characteristics is only one aspect of an exposure assessment. Quantification of exposure to the fields in the MRI facility also requires knowledge of time spent in various locations in the facility. Conversations with and observations of technologists indicate that most time is spent outside the MR examination room that contains the static field magnet. Time is spent in the control room and elsewhere in the facility unless a patient is being brought into the exam room, prepared or assisted. When an MRI procedure is taking place, the technologists typically only enter the operating facility for a few minutes per procedure. The majority of time is spent at the control console. Procedures to assess time spent at various locations in the facility were tested during the procedure evaluation.

The presence of a large static magnetic field poses certain safety hazards to technologists and personnel performing measurements. The safety procedures described here were implemented during the procedure evaluation.

Figure 1.1: Floor plan and work areas at the OHSU MRI facility.

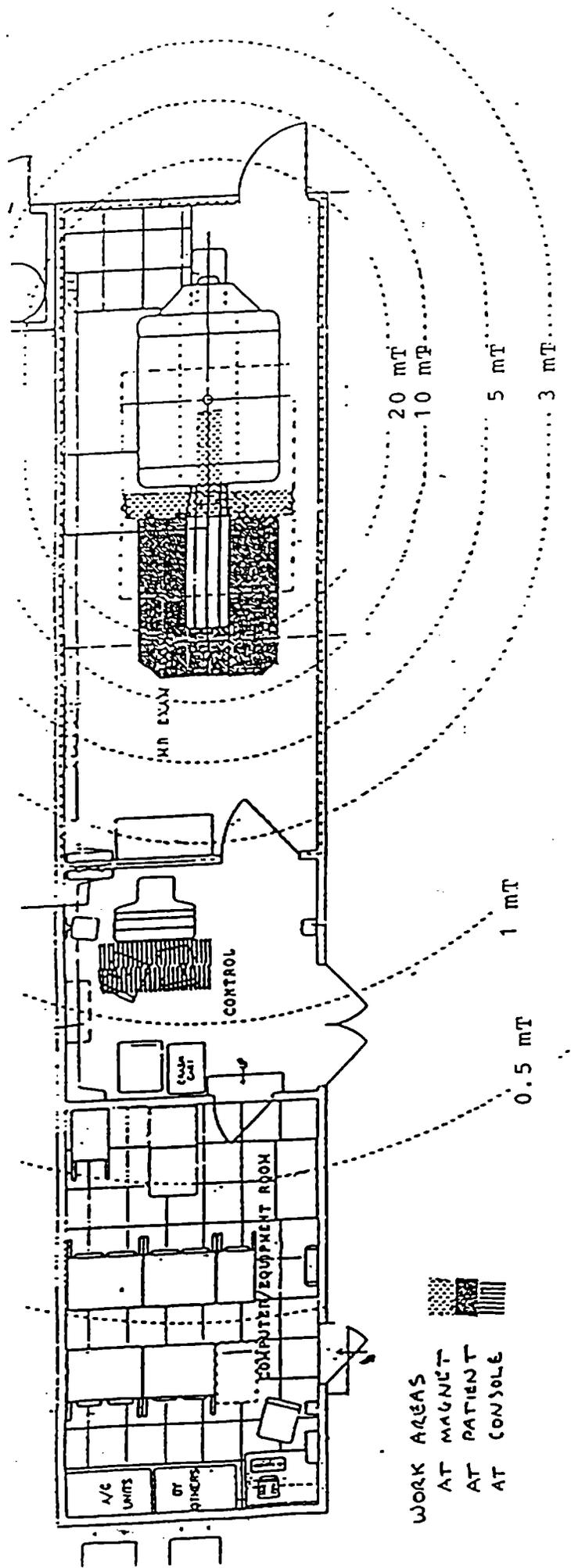
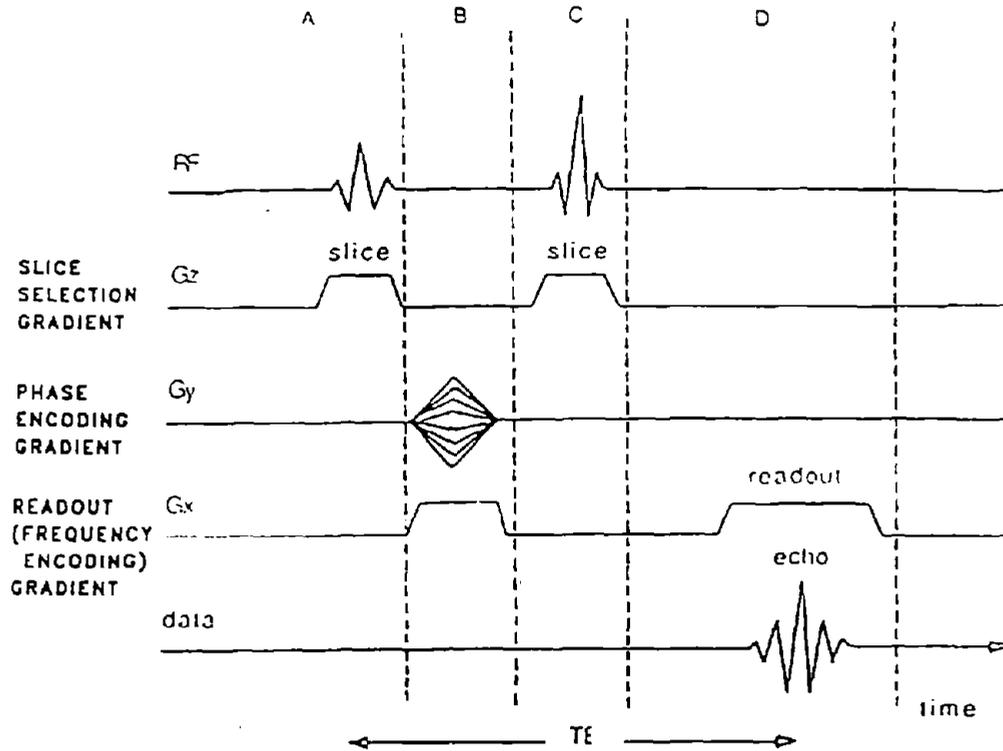


Figure 1.2: Simplified spin-echo pulse sequence with echo time TE. Pulse sequence description: A) Slice selection gradient applied along static field axis (z-axis) simultaneously with RF excitation pulse; B) Phase-encoding gradient applied in steps along vertical axis (y-axis) and frequency-encoding gradient applied along horizontal axis (x-axis); c) Reapplication of slice selection gradient (z-axis) with simultaneous RF pulse; and d) Application of readout (frequency-encoding) gradient along x-axis.



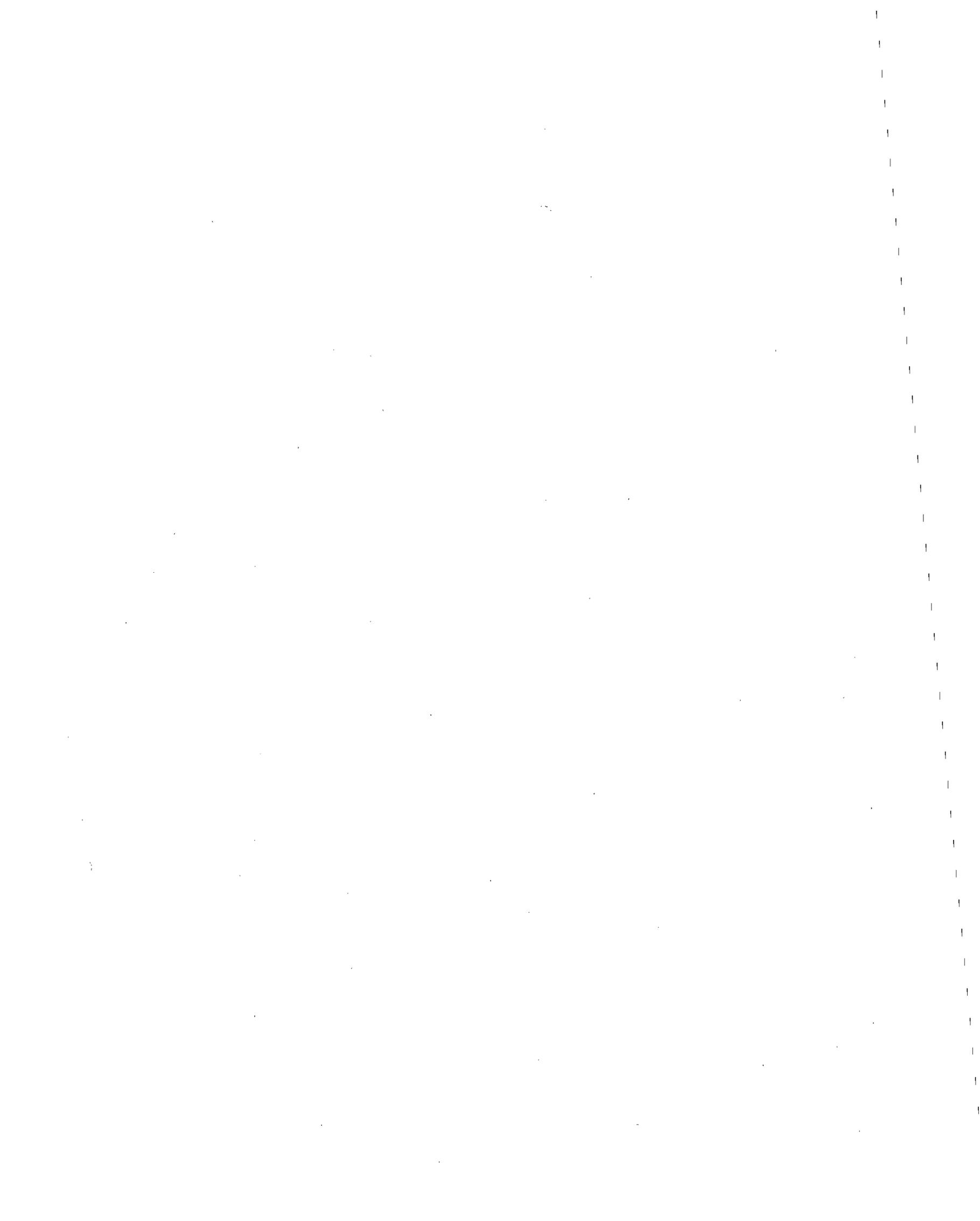
2.0 Methodology for Study Measurements

2.1 Work Areas

The seven specific areas where MRI technologists spend time in the MRI facility are shown on the facility floor plan of Figure 1.1. The seven areas include three specific work stations and four more general areas. These are listed in Table 2.1 along with an operational definition of the areas for use in activity observations. To develop an exposure estimate, field measurements and estimates of time spent are required for all areas. For purposes of observation and field measurements, the following definitions applied: 1) "at the magnet" is in the magnet bore or within 0.5 m of the magnet face; 2) "at the patient" is within 1.0 m of the patient or patient table but not "at the magnet"; and 3) "at console" is sitting or standing within 1.0 m of the console. The distance from an object is measured from the center of the body to the object. "Other areas" refer to areas in the MRI exam or control room that are not included in the specific locations above. Identification of the specific areas was based on observations and conversations with technologists at one facility. The selected areas include work stations where stationary tasks are performed for extended periods (> 30 sec) or where the static fields are exceptionally high. Additional work stations meeting the duration requirement could be identified at other facilities and included in field characterization measurements and time/location observations. The measured fields are discussed in terms of work areas within the MRI facility.

2.2 Measurement Locations

Specific locations for measurements within each of the seven work areas are shown on Figure 2.1. Measurements were made at a total of 25 locations: 13 in the MRI exam room, 6 in the control room, 3 in the computer room, and 3 in the passageway outside the control room (other rooms). For safety reasons, a nonconducting plastic pipe with 0.5 m markings was used to locate measurement locations. Measurement locations were marked on the floor with removable tape so that repeat measurements could be made for different operating conditions. The locations were identified by a number and by their coordinates relative to an origin on the floor at the center of the magnet face as shown in Figure 2.1. In keeping with nomenclature used in MRI facilities, the positive z-axis extended from the origin through the patient table. The x-axis was horizontal with the positive x-axis 90° counter clockwise from the positive z-axis. The positive y-axis was vertical.



With one exception in the MRI room, field measurements at all locations were made at heights of 0.8, 1.1, 1.4 and 1.7 m corresponding roughly to pelvic, chest, neck and head regions. At the patient table, measurements were made along the table (z-axis) at distances of 0.0, 0.3, 0.6 and 0.9 m from the face of the magnet. Measurements of ELF, VLF and LF fields could be made at four heights because of the availability of four sensors. At locations where the single Hall effect probe was used, measurements were made at the four heights sequentially before moving to the next measurement location. The single RF sensor was only used at a few locations, primarily in the bore of the magnet.

2.3 MRI Operating Conditions

The static field measurements were made with the MRI signals off. Most of the gradient field measurements were performed with the MRI producing a spin-echo sequence with a repetition time of approximately 65 ms. The effects of different image sequence parameters on field measurements were investigated briefly by changing the field-of-view (FOV) and slice thickness (t) parameters.

Interference by the RF pulses with the gradient field measurements mandated that the RF pulses be fully attenuated during gradient field measurements.

Initial plans called for investigation of various pulse sequences and MRI protocols. This proved to be overly ambitious as instrument malfunctions and measurement difficulties impacted the schedule. Therefore, the gradient field characterization was limited to essentially one pulse sequence.

Cursory radio frequency (RF) measurements were made for different pulse sequences: spin echo, spoiled gradient and fast spin echo. A body coil was used for most measurements. A water phantom was inserted in the MRI magnet to simulate a patient.

2.4 Multiwave™ System

A portable Multiwave™ System developed by Electric Research and Management, Inc. (ERM) was used for measuring static and gradient fields in the ELF-VLF-LF range (5 Hz - 300 kHz). The system that was employed had previously been used to measure the electrical environment of electrical transportation systems. The portable Multiwave™ System is shown in Figure 2.2. The system utilizes an 80386-

microprocessor based laptop computer operating with ERM Wave-C wave capture software. Analyses were performed with the companion Wave-A analysis software.

The Multiwave™ system was manually triggered to capture waveforms every five seconds over sufficient time to capture at least five waveforms at each measurement location. A waveform capture event entails digitizing the input signal from a sensor for a specified number of samples over the period of the waveform. The period of the waveform is determined by the base frequency selected for sampling: for example, a base frequency of 5 Hz produces a 200 ms period and fast fourier transform (FFT) analysis of the data provides magnitude and phase for the 5 Hz base frequency and its harmonics. The number of samples in a period determines the highest harmonic for which reliable results are available in an FFT analysis: for example, with a base frequency of 5 Hz and 2048 sample points per waveform the maximum harmonic frequency that can be reliably characterized is $5 * 2048 + 2 = 5120$ Hz.

In the Multiwave™ system there were two analog-to-digital data acquisition boards with different base frequencies and sample points per waveform. Board 1 with a 1 Hz base frequency and 128 sample points per waveform was used to capture slowly varying pre-processed signals such as broadband VLF and LF magnetic field magnitude and RF signal intensity from the recorder output of the RF meter. Board 1 was also used for the static field Hall effect probe. Board 2 employed a base frequency of 5 Hz with 2048 sample points per waveform. It was used to capture ELF waveforms from the air coil induction sensors. FFT analyses were performed on the waveforms captured by Board 2.

The use of the Multiwave™ system internal clock as a time reference for sampling resulted in slightly different sampling frequencies than nominally specified: 128.01 Hz actual versus 128.0 Hz ideal sampling frequency for Board 1 and 10.2564 kHz actual versus 10.240 ideal for Board 2. A deviation from ideal sampling frequency can cause an error in the FFT. The slight deviations for Boards 1 and 2 were not significant in this respect.

Ideally, an external trigger from the MRI pulse sequence would provide synchronization of the wave capture process with the MRI pulses. As configured, this Multiwave™ System did not have an external trigger capability. The base frequency for wave capture was therefore set at 5 Hz, so that several MRI pulse trains could be recorded during the 200 ms period associated with one wave capture. This was

successful, and allowed approximately three sets of gradient field pulses to be captured during one 200 ms sampling period. The periodicity of the MRI signal in this case was about 65 ms. The 5 Hz base frequency with 2048 sample points per waveform allowed analysis of harmonics up to approximately 5000 Hz.

Waveform data were stored on hard disk for later analysis. The filenames associated with various measurement conditions and locations are tabulated in Appendix A. Samples of data file summary descriptions generated by the Wave-A software are also included in Appendix A for each type of measurement. The magnitude, frequency spectrum and time derivative of the field (dB/dt) were determined from manipulation of the captured waveform data. The sensors and data acquisition of the Multiwave™ System were calibrated by the manufacturer prior to the measurements. The Multiwave™ System was also operated in a survey mode where a sampled waveform could be viewed directly. This was particularly useful when measuring static fields.

The control and interface unit of the Multiwave™ System would have been affected by the large static field in the MRI exam room. Therefore, it was located in the passageway outside the control room where the static field was less than 1 mT. Long cables connected the sensors to the Multiwave™ System.

2.5 Static Field Sensor

One triaxial Group 3 Technology, Ltd. Hall effect probe was used to measure the large static field from the MRI magnet. The probe and associated amplifier/interface module are shown in Figure 2.3. The probe amplifiers and interface circuits were housed in a separate module located in the control room outside the high field area of the MRI room. The probe was mounted by means of Velcro strips at one of several heights (0.8, 1.1, 1.4, 1.7m) on a plastic pipe stand moved to various locations. The orientation of the probe was kept constant as it was moved from location to location. The probe was also set on the MRI patient table to record fields along the axis of the MRI magnet. A few initial measurements with the Hall effect probe indicated it was immune to interference from the gradient field and radio frequency pulses. Also slight motion when the stand was held by hand, as opposed to resting on the floor, did not affect the measurement. This is not surprising, since the Hall effect probe has a small area and does not depend on a field induction to sense the field.

During or prior to systematic measurements of the static field in the MRI facility, a malfunction occurred in one of the Hall effect probe channels resulting in spurious gains for that channel (channel A, vertical field). When the malfunction occurred was not apparent during data collection. However subsequent examination of the data indicated that the data collected from that channel during mappings of the static field were affected. Apparently a gain setting relay was frozen in the presence of the static field in the control room, leading to recorded fields in Channel A that were too large by a factor of ten. Reducing these fields by a correction factor of 10 resulted in field values consistent with earlier measurements.

The Hall effect probe also has a temperature-dependent field offset which can be compensated for in data analysis. The temperature of the probe for each axis was recorded along with the field measurements. However, no attempt was made to correct the field data in this pilot set of measurements because of two factors. First accurate determination of the initial offset during these measurements was hampered by the need to remain in the MRI facility where the background field from the MRI magnet exceeded 0.1 mT. Initial estimated offsets for the Hall probes were -3.47, -2.13 and 0.36 mT for the x,y and z probes respectively. Second, examination of the data collected during field mapping indicated an offset of approximately 5 mT in the malfunctioning channel. These factors limited the usefulness of the probe in fields less than about 20 mT and decreased confidence in any offset correction for this set of data.

2.6 Air-core Induction Sensors

Four sets of triaxial air-core induction coils manufactured by ERM were used to sense magnetic fields with frequencies in the range of 5 Hz to 300 kHz. The triaxial sensors were contained in a 2.5 cm cube. Four cubes were mounted in a plastic pipe at heights of 0.8, 1.1, 1.4, and 1.7 m above the base of the pipe. The preamplifiers that integrate and condition the signal from the coils were also located in this pipe or measurement "staff". The staff is shown in Figure 2.2. The staff was generally used in a vertical position, but was also laid horizontally on the MRI patient table to measure fields at varying horizontal distances from the magnet. The cable connector was used as a reference to orient the staff in a fixed direction for all measurements.

The induction coil sensors and preamplifiers had been used previously in transportation environments but had not been tested in the MRI environment. Two problems arose with the preamplifiers

for these sensors. First, the preamplifiers were not sufficiently shielded to prevent electromagnetic interference (EMI) from the 63 MHz RF MRI pulses. Thus, it was necessary to perform all measurements with the induction coil sensors with the MRI RF pulses fully attenuated. This requirement did not affect measurements of the gradient fields but precluded any simultaneous measurement of both gradient and RF pulses.

Of more significance for the measurement of gradient field pulses was the high pass filter in the preamplifier. The low frequency cutoff for this filter was 35 Hz and distorted the response of the instrument to square pulses of the type associated with gradient fields. Recorded waveforms from an induction sensor in response to square field pulses are shown in Figure 2.4. The square field pulses were produced with a function generator and a pair of Helmholtz coils. In order to compensate for the measured frequency response characteristic of the high pass filter and produce a more realistic waveform, adjustments were made to frequency component magnitudes and phase angles in the fast fourier transform (FFT) of the recorded wave. The inverse transform of the adjusted FFT was then used to produce a waveform in the time domain that more closely represented the actual magnetic field pulses. Adjusted waveforms for the square pulse fields are also shown in Figure 2.4. The waveforms for all gradient measurements made in the MRI facility were adjusted in this manner for visual examination, analysis and presentation. An example of an unadjusted and adjusted gradient field waveform is shown in Figure 2.5.

The time derivative of the gradient field waveform, dB/dt , was constructed from the captured waveform for each axis: an FFT of each waveform was performed; then the FFT was differentiated; and finally the inverse transform of the differentiated FFT produced a dB/dt waveform for each component of the field. The magnitude of the total time derivative of the field, $|dB/dt|$, for a waveform was calculated as the resultant of the dB/dt waveforms from the three axes. Both the rms magnitude of $|dB/dt|$ and the peak instantaneous $|dB/dt|$ within a waveform were considered in analysis.

2.7 Broadband RF Field Strength Meter

A Holaday Instruments Model HI-3002 Isotropic Broadband RF Meter was used to measure RF electric and magnetic fields with two different probes. A Holaday STE E-field probe was used to measure RF electric fields. A Holaday CH H-field probe was used to measure RF magnetic fields. Both probes were isotropic and had a 6.1 m (20 ft) cable. The Holaday Model HI-3002 RF meter and probes were

provided by NIOSH. The extra cable length required to keep the meter outside the high static field area was supplied by the manufacturer. Calibration of the instrument and probes with cables was performed by Holaday Instruments prior to the measurements. RF levels were observed using the rms and peak-hold function of the detection circuit.

Originally plans called for the 0-1 volt analog recorder output from the RF meter to be recorded by the Multiwave™ System for a set of pulse sequences. However, Holaday reported that the response time of the recorder output was about 5 ms which severely limited its ability to respond to the MRI square RF pulses, whose widths are of the order of 10 ms. Further limiting this approach to recording RF pulse sequences was the Multiwave system sampling rate for the RF meter channel. The Multiwave™ System was configured to accept the RF meter output in the slow data acquisition board which had a base sampling frequency of 1 Hz with 128 points per sample. Thus, the period between sample points was about 8 ms: clearly too slow to accurately capture the RF pulses. Because of these two limitations, recording of the RF pulse sequences by the Multiwave™ System did not capture RF pulse wave forms during these measurements and it was necessary to rely on manual readings from the RF meter.

Because the static field in the MRI room would affect the Holaday RF Meter, it was located in the control room. When measurements were made in the MRI exam room, the sensor cables passed through the entry door, thus compromising the integrity of the RF shielding. This was not of concern since the shielding is intended to prevent unwanted RF signals from interfering with the imaging process for a patient.

When measurements were made in the MRI room, the RF probes were mounted with Velcro strips on the same plastic pipe stand used for the static field Hall probe. However, many measurements were also made on the patient table and in the bore of the magnet where the probes were held or laid down.

2.8 Power Frequency Electric and Magnetic Field Survey Measurements

An EMDEX-C meter manufactured by Electric Field Measurements Co. was used to survey power frequency electric and magnetic fields in the console and computer rooms. This is a handheld microprocessor-based instrument with digital display and a bandwidth of 40 to 400 Hz. For electric field measurements the meter was held on an 0.4 m insulated rod to keep it away from the influence of the observer.

measurements the meter was held on an 0.4 m insulated rod to keep it away from the influence of the observer.

2.9 Performance Tests

Prior to performing extensive measurements, the performance of the instruments and sensors was verified in the static and RF fields present in the MRI exam room. Responses of the various sensors was noted with the gradient and RF pulse sequences on and off. The effects of motion on the magnetic field sensors was also observed.

2.10 Photographs

Photographs were taken of measurement areas and sensor deployment. Although care was taken not to use the camera in static fields greater than about 5 mT, the camera malfunctioned after several photographs were taken in the control room/MRI room area. Replacement of the battery after leaving the facility returned the camera to normal operation.

2.11 Time and Location Monitoring

Two time and motion monitoring methodologies were tested during the evaluation: a simple log with manual entries and a computerized record, based on bar-code reader entries.

For the manual entry log, a form similar to that shown in Figure 2.6 was used by an observer to record time spent in the seven work areas. A small digital clock displaying hours and minutes was fixed to the non-metallic clipboard that held the form. To more accurately obtain time readings, a digital watch displaying seconds was also used.

A second procedure that was tested for time/location monitoring utilized the Videx® TimeWand I Portable Bar Code system. The TimeWand I is a portable bar code reader about the size of a small pocket calculator. It reads bar code labels and stores the label and date and time in memory. The smallest time interval recorded by the TimeWand® System is 16 seconds. The information in the TimeWand® memory is downloaded to a personal computer where it can be analyzed. Documentation on the programs used to download the TimeWand® and generate time/location reports is included in Appendix B.

During observations with the TimeWand® system, each person was assigned a set of bar codes, one for each work area. The bar codes for all individuals were arranged on the scan sheet shown in Figure 2.7. The observer scanned the appropriate bar code for an individual and work area as the individual entered that work area. In this way a time-stamped record of locations was generated. Because of the high fields near the MRI magnet, the portable bar code reader was kept in the control room to ensure that the memory was not corrupted and that the TimeWand® was not physically attracted in the static field. The data from the TimeWand® was downloaded and a report on the amount of time individuals spent in various work areas was generated.

Table 2.1: MRI facility work areas and measurement locations

Work Area	Description	Preferred Measurement Location
Control room		
1. At console	Within 1.0 m of console	At 0.5 m intervals, 0.5 m from console
2. Other areas	Areas not included in 4. above	At 1.0 m intervals in work area
MRI exam room		
4. At the magnet	In the bore or within 0.5 m of the magnet face	At 0.5 m intervals, 0.5 m from magnet face
5. At the patient table	Within 1.0 m of the patient table	At 1.0 m intervals, 0.5 m from patient table
6. Other areas	Areas not included in 4 and 5 above	At 1.0 m intervals
6. Computer room	In the computer room	At 1.0 m intervals in work area
7. Other rooms	In other rooms of the facility	At 2.0 m intervals in work area

Figure 2.1: Magnetic field measurement locations at the Oregon Health Sciences University MRI Facility.

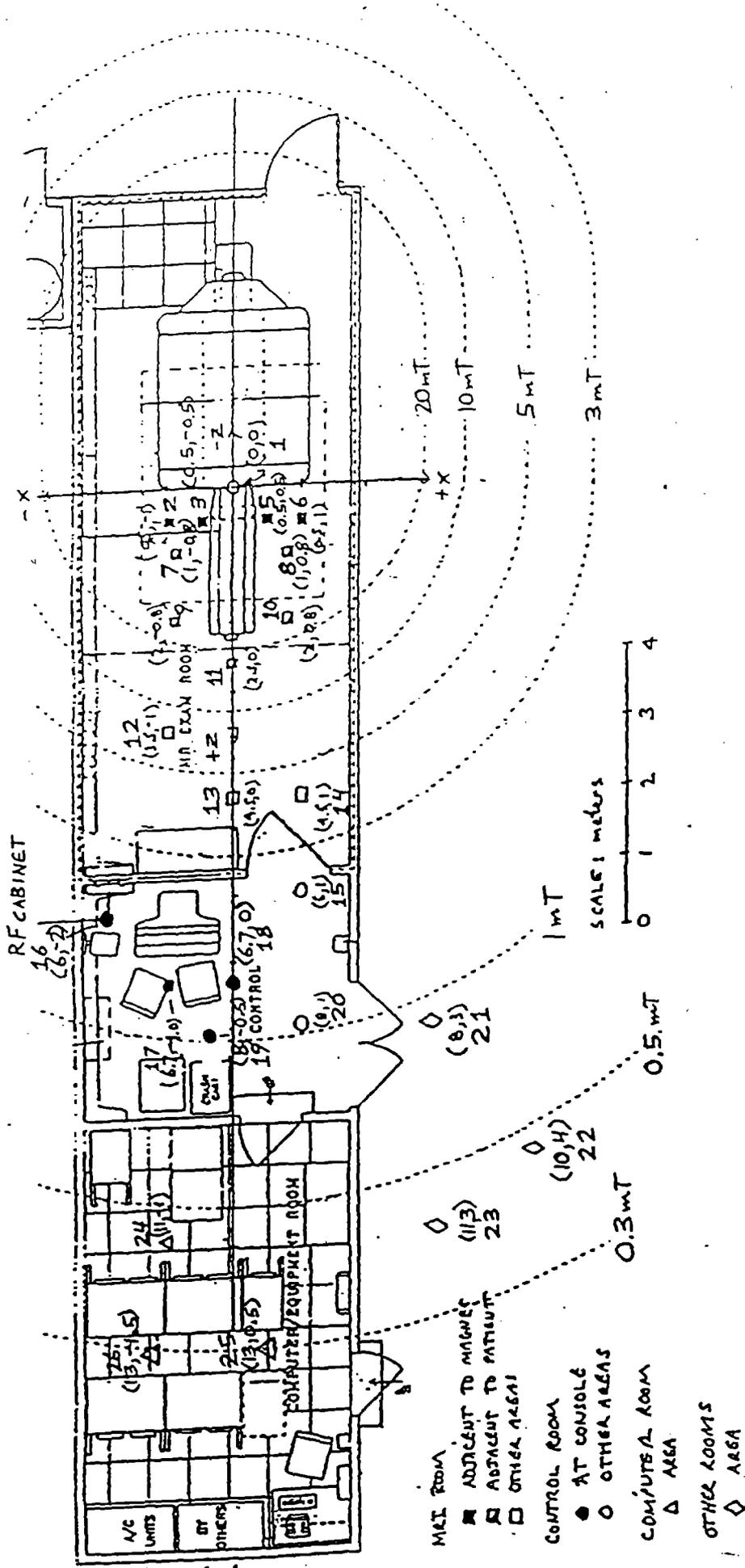


Figure 2.2: Portable Multiwave™ System with air coil induction sensor staff. (Hall effect probe and amplifier/interface module is on left.)



Figure 2.3: Multiwave™ System Hall effect probe and amplifier/interface module.

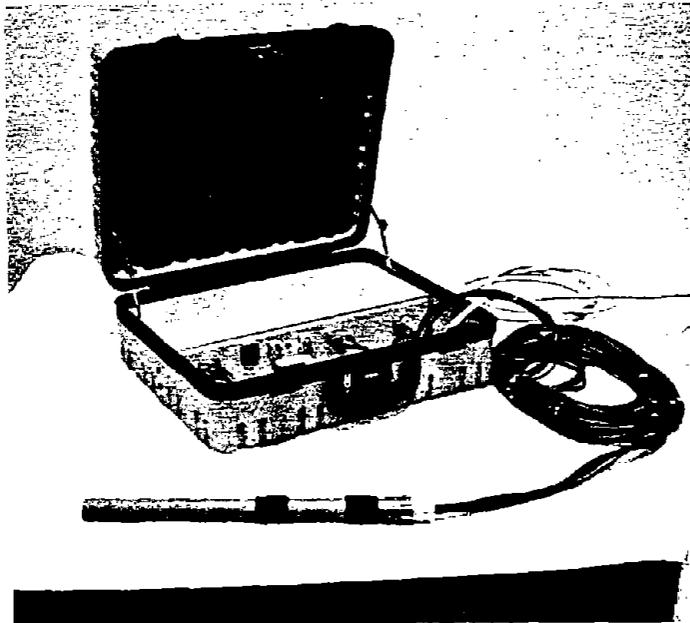
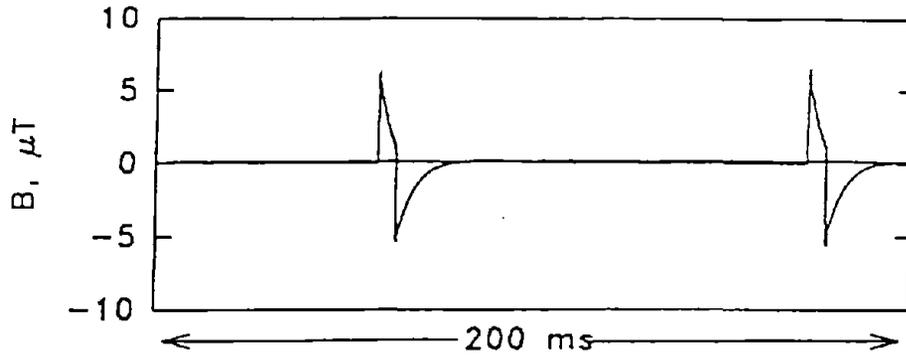


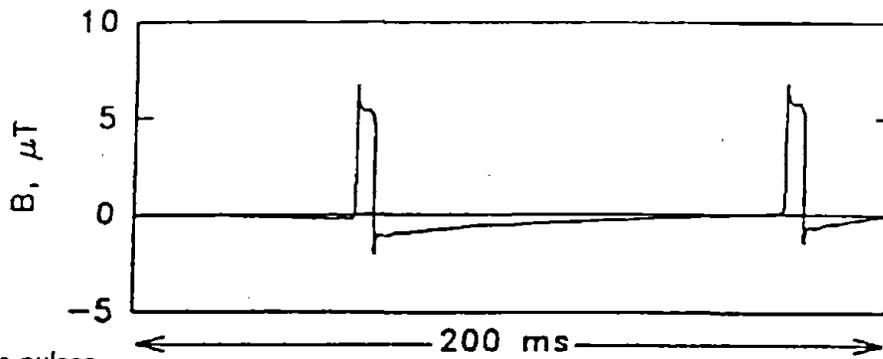
Figure 2.4: Unadjusted and adjusted response of Multiwave™ System air-core induction sensor and preamplifier to square pulse fields: a) 4 ms pulses; b) 10 ms pulses.

a) 4 ms pulses

Unadjusted:

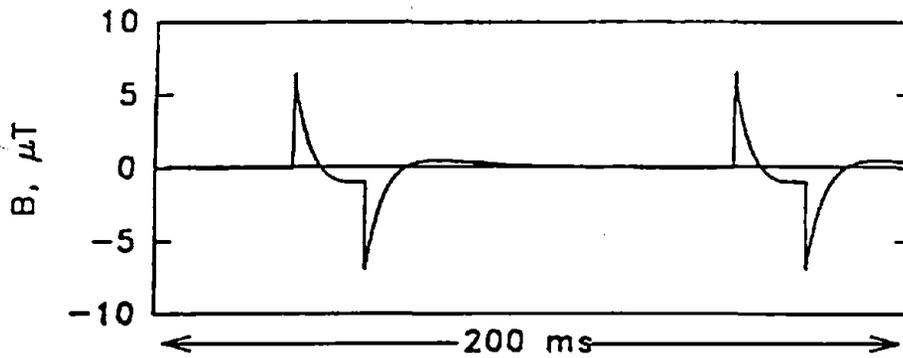


Adjusted:



b) 10 ms pulses

Unadjusted:



Adjusted:

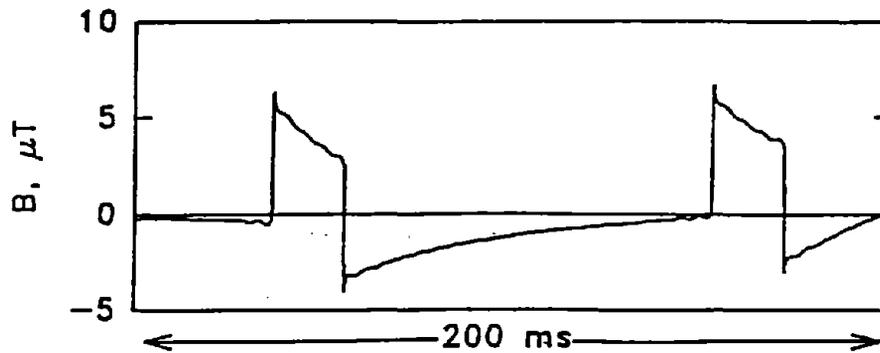
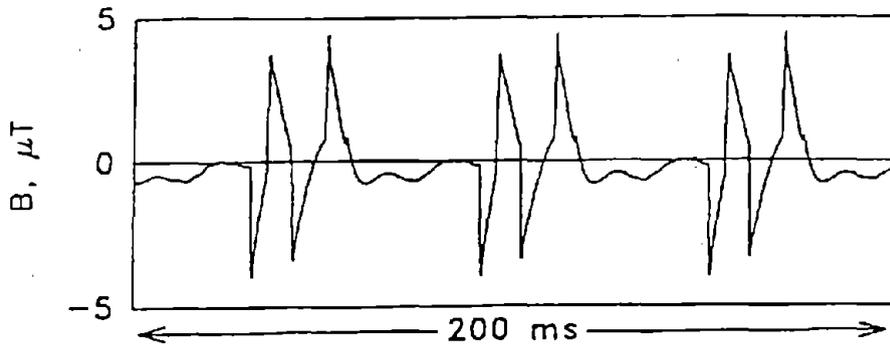
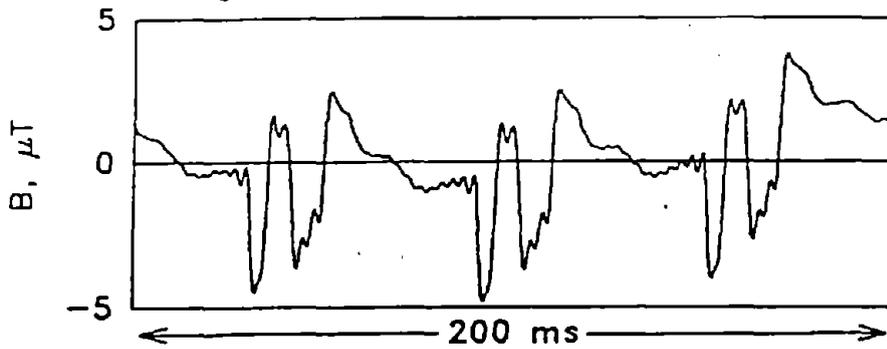


Figure 2.5: Unadjusted and adjusted response of Multiwave™ System air-core induction sensor and preamplifier to typical gradient field waveforms.

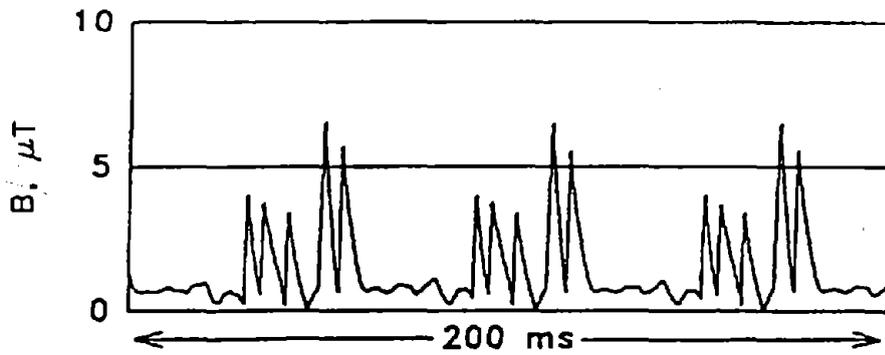
Unadjusted waveform, single axis



Adjusted waveform, single axis



Unadjusted waveform, resultant



Adjusted waveform, resultant

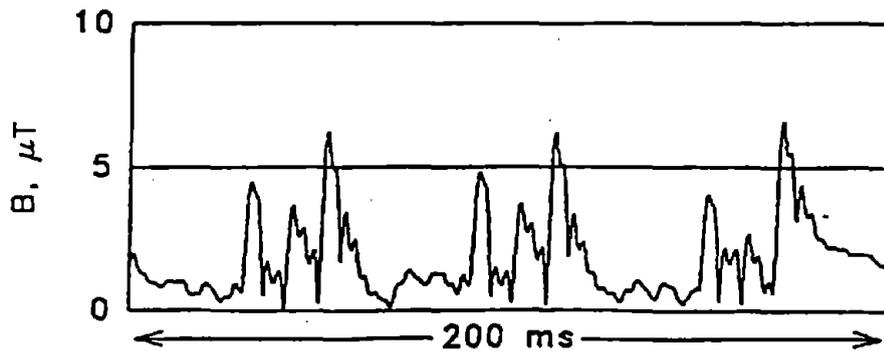


Figure 2.7: MRI Facility Time/Location Bar-code Scan Sheet

MRI Location Scan Sheet

Protocol

Unknown #1	 * P 0 1 *	Unknown #4	 * P 0 4 *
Unknown #2	 * P 0 2 *	Unknown #5	 * P 0 5 *
Unknown #3	 * P 0 3 *	Unknown #6	 * P 0 6 *

<u>Location</u>	<u>Person 1</u>	<u>Person 2</u>	<u>Person 3</u>
Control Room	 * 0 1 1 *	 * 0 2 1 *	 * 0 3 1 *
@ Console	 * 0 1 2 *	 * 0 2 2 *	 * 0 3 2 *
MRI Room	 * 0 1 3 *	 * 0 2 3 *	 * 0 3 3 *
@ Patient	 * 0 1 4 *	 * 0 2 4 *	 * 0 3 4 *
@ Magnet	 * 0 1 5 *	 * 0 2 5 *	 * 0 3 5 *
Computer Room	 * 0 1 6 *	 * 0 2 6 *	 * 0 3 6 *
Other Rooms	 * 0 1 7 *	 * 0 2 7 *	 * 0 3 7 *
End	 * 0 0 0 *	Error	 * 0 E R *

3.0 Results

3.1 Static Field

Initial tests with the Hall effect probe were performed to verify the performance of the instrument in the MRI environment. The Hall effect probe was placed at a height of 1.1 m at 0.5 m from the face of the MRI magnet and 0.5 m from the axis of the MRI magnet (Location 05). The magnitude of the field for each channel of the Hall effect probe was manually recorded for three successive wave capture events.

The average results for the three readings of the static magnetic field for various operating conditions of the MRI system and for different probe mounts are given in Table 3.1. The differences between static field values for conditions with RF and gradient fields on and off were within the uncertainty of repeated measurements for the same condition ($<\pm 2\%$). Resultant static fields measured with the probe stand resting on the floor or held in the hand were also within this uncertainty ($<\pm 2\%$). Slight differences in orientation of the probe account for the difference in component field magnitudes between the handheld and floor-mounted probe cases. These results indicate that static field measurements with the Hall effect probe were not significantly affected by the MRI RF or gradient pulse sequences. Also, whether the probe mounted on the stand was resting on the floor or held in the hand did not appear to influence the resultant measurements.

Measurements of the static field at several locations in the MRI room were performed at the four staff heights. The measurements (with A-channel corrected) at 1.1 m height have been overlaid on the field contours provided by the MRI manufacturer in Figure 3.1. The measured values are consistent with the contour values. Measurements with the Hall effect probe in fields less than 15 mT were considered invalid because of the uncertainty in signal offsets that was not compensated for in the analyses.

The variation of static field as a function of height at selected locations is shown in Table 3.2. As expected the variation with height was not great in work areas near the patient table: less than $\pm 8\%$ from 0.8 m to 1.4 m height everywhere except at the end of the patient table where it was +10% and -16%. The one exception at a height of 1.1 m at Location 07 (1, -5 m) seemed spurious and may have been due to a transcription error in recording the data.

A small Hall probe personal dosimeter manufactured by Seiko was worn by Dr. Joe Bowman of NIOSH during the measurements. Both static and ac fields could be measured with the dosimeter. However, only the static field mode seemed to be functioning during these measurements. Comparison of readings with this device were in agreement ($\sim 10\%$) with those of the triaxial Hall probe in the large static fields near the magnet bore: 124-133 mT for the dosimeter and 138 mT for the large triaxial probe.

The Seiko dosimeter also stores a time-integrated exposure for static field in units of mT-hr. While wearing the dosimeter for 5.37 hr., Dr. Bowman recorded an exposure of 29.01 mT-hr for a time-weighted average exposure of 5.2 mT. The dosimeter was not included in the proposed instruments for evaluation, so tests beyond these were not performed with it.

3.2 Gradient Fields

Several tests were performed to verify the performance of the air-core induction sensors and to characterize the ELF magnetic fields due to MRI gradient pulses and power frequency currents.

Initial tests indicated that the MRI RF fields interfered significantly with ELF measurements. Near the MRI magnet, operation of the MRI RF pulse sequence increased the signal from the air core sensors by a factor of ten or more over that with the gradient fields alone. Consequently, all gradient measurements with the air-core induction sensors and the Multiwave™ System were made with the RF pulses fully attenuated. After the measurements, the manufacturer (ERM) shielded the induction coil preamplifiers and the interference problem was reportedly eliminated.

Movement of the induction coil sensors in large static magnetic fields can induce strong signals. Therefore, the effect of holding the sensor staff instead of mounting it in a stand was investigated. The results were dramatic: the rms resultant field for the entire waveform (5-5000 Hz) measured at 1.1 m height at 0.5 m in front of the magnet face and 0.5 m from the axis of the magnet (Location 03) was 2.2-2.3 μ T with the probe in the stand and 20-40 μ T with the probe held in the hand. Examination of the waveform indicated a large low frequency field component at 5-20 Hz for the hand-held case. This is attributed to movement of the coils in the 160 mT static field at this location. All subsequent measurements were made with the staff mounted in its stand.

Measurements of gradient fields were made with the MRI producing a simple spin-echo pulse sequence with a repetition rate (TR) of about 65 ms. A spin-echo pulse sequence is shown schematically in Figure 1.2. The RF pulses were suppressed during measurements. Because the MRI system had to be turned off several times during the measurements to prevent overheating, exactly identical pulse sequences may not have been present for the entire day.

Three orthogonal gradient field waveforms captured at four heights at one location are shown in Figure 3.2. The adjusted waveforms shown in Figure 3.2 are typical of others obtained within a few meters of the magnet. There is a distinct pattern to each waveform but it is difficult to interpret the sources of the pulses because the gradient field components are comprised of fields from several different coils in the magnet bore. However, if data on the simple geometry of the gradient coils and the current pulse sequence were available, computation of the field components from each coil could be performed. A time

reference synchronized to the MRI pulse sequence would also assist interpretation of waveforms. However, to identify pulses or components in the measured fields with a particular gradient pulse in the sequence would still be difficult. As the measurement location changes, the components of the fields from the different coils change. Therefore, the description of the ELF gradient fields presented here focuses on the resultant field. Data for both the rms resultant field computed over a waveform and the instantaneous peak field within a waveform are presented.

The resultant field waveforms from the four sets of measurements as a function of height in Figure 3.2 are combined in Figure 3.3. Similar resultant waveforms were present at each height, with the largest instantaneous magnitude ($7\mu\text{T}$) present at 1.1 m and 1.4 m height for this case. The largest rms gradient field of $2.4\mu\text{T}$ was also present at the 1.1 m and 1.4 m heights.

The frequency spectra for the resultant waveforms in Figure 3.3 are shown in Figure 3.4. The frequency spectra at the different heights were similar, with slightly varying magnitudes for the different components. The strongest field components varied somewhat with location. However, near the magnet the largest field components were generally at 15 and 65 Hz for this pulse sequence. For other measurements, the peak components were similar but could vary by the 5 Hz base frequency. At locations well away from the face of the magnet, the predominant frequencies were 60 and 180 Hz, corresponding to the first and third harmonics of the power frequency.

The frequency spectra in Figure 3.4 are shown to the 80th harmonic or 400 Hz. Examination of the frequency spectra out to higher harmonics indicated that at a distance of 0.6 m from the magnet along the patient table, harmonics at frequencies higher than 400 Hz were less than $0.1\mu\text{T}$. At the face of the magnet, field components at frequencies greater than 1500 Hz were less than $0.1\mu\text{T}$. To demonstrate the lack of field components at higher frequencies, the harmonic content out to 5000 Hz is shown in Figure 3.5 for the sensor at 1.1 m height at 0.5 m from the magnet face and 0.5 m off the axis (Location 03).

The relatively low fields at frequencies above 400 Hz, were further reflected in the measured rms fields in the VLF (3-30 kHz) and LF (30-300 kHz) bands shown in Table 3.3. The rms VLF fields decreased rapidly with distance from the magnet: going from $5.2\mu\text{T}$ at the face of the magnet to about $0.02\mu\text{T}$ at a distance of 0.9 m along the patient table. Similarly, the rms LF field dropped from about $0.3\mu\text{T}$ at the face of the magnet to less than $0.01\mu\text{T}$ at a distance of 0.9 m.

The time derivatives of the gradient field waveforms in Figure 3.3 are shown in Figure 3.6. The time derivative, dB/dt , was calculated as the resultant of the time derivatives for each component of the gradient field waveforms. The instantaneous magnitude of the time derivative within a waveform varied somewhat with height: the maximum instantaneous peak value of 13 mT/s was at 1.1 m height and the

minimum instantaneous peak value was 7 mT/s at 1.7 m height. The rms magnitude of the time derivative (5-5000 Hz) across the waveform for three pulse sequences was 2.1 mT/s at 1.1 m height and 1.5 mT/s at 1.7 m height.

The effects of attenuation of the spin-echo pulse sequence gradient field level on the measured resultant gradient field waveforms and frequency spectra at one location are shown in Figures 3.7 and 3.8. For these observations the MRI operator successively attenuated the maximum gradient field setting by factors of two and four. As the field was reduced, changes in the waveforms and frequency spectra were apparent. However, the reduction in the rms and peak gradient fields was not linear.

The spatial distribution of the gradient fields was measured along the patient table and throughout the MRI facility. The measured resultant gradient fields and resultant time derivative dB/dt of the gradient fields along the patient table are given in Table 3.4. Both rms values for a waveform and the peak value within waveforms are given. Lateral profiles of the average resultant fields and time derivatives of the field are shown in Figure 3.9. The peak gradient field fell from 87.5 μT at the face of the magnet to 2.9 μT at a distance of 0.9 m. The peak field derivative fell from 161 mT/s at the bore mouth to 11 mT/s at a distance of 0.9 m from the magnet along the patient table. The gradient field waveforms, frequency spectra and dB/dt wave forms as a function of distance along the patient table are shown in Figures 3.10, 3.11, and 3.12, respectively. Although the field magnitudes attenuated with distance, there were no large changes in the frequency spectra: the average total harmonic distortion (THD) referenced to the 5 Hz base frequency was 555% at the face of the magnet and 594% at 0.9 m from the magnet.

The four-sensor ELF measurement staff was deployed at numerous locations to measure gradient fields at four heights. The rms gradient fields from these measurements are tabulated in Table 3.5 and shown graphically near the patient table on a contour plot in Figure 3.13. The contour plot emphasizes how rapidly the rms gradient fields fall off with distance from the MRI magnet. Beyond 1 m from the magnet, the rms gradient fields are less than 1.0 μT . At the end of the patient table, 2.5 m from the magnet face, the gradient fields are about 0.13 μT . At distances greater than this, localized sources determine field levels in the ELF frequency range. For example, at a location in the corner of the control room near the RF cabinet and where cables pass through the screened enclosure, field levels ranged from 0.4 to 1.3 μT .

Field levels in the ELF range observed in the MRI computer room were higher than those in the control room and part of the MRI exam room. Measured resultant fields in the range of 0.2 to 1.9 μT were observed in the computer room, depending on height and location. These levels did not change significantly ($<0.1 \mu T$) when the MRI pulse sequence was turned off. In addition, the fields at these locations were predominantly at 60 Hz. Thus, fields in the this area (and in the immediately adjacent hall

area) were due to 60-Hz power consumption in this area that was not dependent on operation of the MRI system.

The effects of pulse sequence characteristics on the gradient field levels were investigated briefly with the measurement staff laid along the patient table. Both the field-of-view (FOV) and slice thickness (t) parameters were changed: 1) FOV = 8 cm, t = 3 mm; 2) FOV = 48 cm, t = 3 mm; and 3) FOV = 48 cm, t = 2 cm. The rms resultant fields for the three pulse sequences as a function of distance from the magnet face are shown in Figure 3.14 and listed in Table 3.6. For all pulse sequences, the resultant field fell off quickly with distance, dropping to about 0.5 μ T at a distance of 0.9 m from the magnet. The resultant field waveforms, frequency spectra and $|dB/dt|$ waveforms recorded for each pulse type are shown in Figures 3.15, 3.16 and 3.17, respectively, for a location 0.3 m from the magnet face. Increasing the FOV parameter reduced the magnitude of the fields outside the magnet, while changing the slice thickness did not seem to impact these fields.

3.3 RF measurements

The RF field levels in the MRI exam room work areas were too low to be reliably detected by the Holaday Broadband Survey Meter. When the RF survey probes were placed 90 cm into the bore of the magnet, reliable RF measurements were possible. For example, for the initial spin echo sequence with unattenuated RF pulses present, rms electric field strength readings were 3×10^3 V²/m at a location 90 cm into the bore versus a non-detectable reading at the bore mouth. The rms magnetic field readings were 2.6 A²/m² 90 cm into the bore versus <0.001 A²/m² at the face of the magnet. RF fields outside the magnet could be detected using the peak hold function of the meter but the readings were not consistent from one sample to the next. Levels in the bore were higher with the body coil than with the head coil. Absorption of RF fields by the presence of an observer was also noted.

3.4 Power Frequency Electric and Magnetic Fields

An EMDEX-C meter was used to survey local electric fields in the console and computer rooms. Electric fields in the console room and elsewhere were at or below the threshold for detection of the EMDEX-C meter: -5 V/m. Near fluorescent light fixtures, electric fields increased to 20 V/m.

Magnetic fields were measured at a few locations very close to cables and cabinets associated with the ac power supplies for equipment in the computer room. Close to cables, fields up to 30 μ T were measured, while in nearby accessible walkways the fields were 0.2-1.0 μ T.

3.5 Time/Location Monitoring

The evaluation protocol called for monitoring the location of one or more investigators during the measurements. Activities associated with measurements entailed more movement and changes in location

than would occur for a technologist during normal facility operation. With the increased level of activity, manual monitoring of more than one person in and out of work areas proved difficult. The 10-second criterion for recording times and durations was difficult to achieve. Also, it was difficult to discern and record periods when the subject was at the various localized work areas within a room, such as the magnet and patient table in the MRI exam room. Therefore, only time in rooms was logged.

Observations of the movements of the project manager over an 18 minute (1080 s) period are shown on the Time/Location Manual Log in Figure 3.18. During this period he changed work areas 21 times. The estimated division of time for this period was: in MRI exam room, 194 s (18%); in control room, 650 s (61%); and in other rooms, 226 s (21%). Estimates of time in each room are approximate because of the uncertainty in the time when locations were changed during the first few minutes.

The use of the TimeWand® bar code system to log time and location data was more successful for the high activity level associated with measurements. One observer was able to track the movements of three investigators in the various work areas for over an hour. The results are presented in Table 3.7, which lists time spent and percent of time spent for each of the seven work areas. During the 68 minutes of observations, there were 305 changes of location for the three individuals. For all three individuals, the most frequented areas were: in the control room and in other rooms. During this period, only about 5% of time was spent at the magnet by the two individuals (Persons 1 and 2) principally involved in conducting measurements. The complete TimeWand® report from this observation period is included in Appendix B.

Table 3.1: Effect of MRI operating condition and probe mount on static magnetic field in millitesla (mT) measured by Hall effect probe. Average of three field values.

MRI Operating Condition	Probe Axis			
Probe axis	x	y	z	Resultant
MRI operating condition				
a) No MRI pulses	7.6	55.9	-126.0	138.1
b) With RF and gradient pulses	7.5	56.2	-125.2	137.4
c) With gradient pulses only	7.4	56.2	-126.0	138.2
Probe mount				
a) In stand	6.4	70.6	-127.3	145.7
b) Handheld	14.1	64.9	-130.5	146.4

Table 3.2: Static field in millitesla (mT) as a function of height above ground at selected locations in MRI exam room.

Location*, m			Description	Height, m			
No.	z	x		0.8	1.1	1.4	1.7
02	0.5	-1.0	At outside edge of magnet face	88.9	90.6	90.1	85.4
03	0.5	-0.5	At magnet and adjacent to patient table	155.5	164.7	165.9	145.2
05	0.5	0.5	At magnet and adjacent to patient table	145.4	147.3	143.2	134.7
07	1.0	-0.5	At patient table	62.3	97.9**	64.9	66.7
09	2.0	-0.5	At patient table	21.7	23.3	23.6	23.9
11	2.5	0.0	At end of patient table	14.8	17.8	18.9	17.5

* Origin at center of MRI magnet face; z-axis along magnet axis; x-axis horizontal and perpendicular to z-axis; y-axis vertical.

** Possible data transcription error. Correction would result in 63.4 mT.

Table 3.3: Magnetic fields in microtesla (rms) in the VLF (3-30 kHz) and LF (30-300 kHz) bands measured along the patient table.

Distance from magnet, m	Frequency Band	
	VLF	LF
0.0	5.2	0.28
0.3	0.48	0.09
0.6	0.17	0.07
0.9	0.02	0.007

Table 3.4: Resultant gradient field and resultant time derivative of gradient field as a function of distance along patient table.

Distance from magnet, m	Resultant gradient field, μT		Resultant time derivative, mT/s	
	$ B _{\text{rms}}$	$ B _{\text{peak}}$	$ dB/dT _{\text{rms}}$	$ dB/dT _{\text{peak}}$
0.0	27.5	87.5	28.0	161.0
0.3	7.8	24.0	6.5	42.5
0.6	2.8	7.1	2.2	13.0
0.9	1.2	2.9	0.9	6.2

Table 3.5: Resultant gradient fields in microtesla (μT) measured in MRI facility as a function of height. Field values are average of three 200 ms sampling periods for frequency range 5-400 Hz.

Location			Description	Height, m			
No.	z	x		0.80	1.10	1.40	1.70
02	0.5	-1.0	At magnet face	1.18	1.29	1.29	1.06
03	0.5	-0.5	At magnet face and adjacent to patient table	2.12	2.35	2.40	1.88
05	0.5	0.5	At magnet face and adjacent to patient table	2.41	2.54	2.25	1.79
06	0.5	1.0	At patient table	1.19	1.22	1.14	0.91
07	1.0	-0.5	At patient table	0.84	0.93	1.20	0.93
08	1.0	0.5	At patient table	0.76	0.79	0.95	0.84
09	2.0	-0.5	At patient table	0.19	0.18	0.20	0.18
10	2.0	0.5	At patient table	0.21	0.20	0.19	0.18
11	2.5	0.0	At head of patient table	0.13	0.13	0.13	0.12
12	3.5	-1.0	In MRI room	0.05	0.05	0.07	0.05
13	4.5	0.0	In MRI room	0.03	0.03	0.04	0.04
14	4.5	1.0	In MRI room	0.03	0.03	0.03	0.04
15	6.0	1.0	At control room/MRI room door	0.03	0.03	0.03	0.04
15*	6.0	1.0	At control room/MRI room door	0.03	0.03	0.03	0.04
16	6.0	-2.0	In control room near rf cabinet	0.38	0.71	1.32	0.06
17	6.7	-1.0	At console in control room	0.07	0.07	0.08	0.08
18	6.7	0.0	At console in control room	0.06	0.05	0.05	0.06
19	8.0	-0.5	In control room	0.09	0.09	0.09	0.08
20	8.0	1.0	In control room	0.14	0.12	0.10	0.10
20*	8.0	1.0	In control room	0.14	0.12	0.11	0.10
21	8.0	3.0	In hall at entry to control room	0.05	0.03	0.04	0.08
22	10.0	4.0	In hall	0.04	0.04	0.05	0.08
22*	10.0	4.0	In hall	0.05	0.04	0.05	0.10
23	11.0	3.0	In hall	0.20	0.18	0.17	0.17
24	11.0	-1.0	In computer room at tape drives	0.21	0.30	0.26	0.51

Table 3.5 continued

Location			Description	Height, m			
No.	z	x		0.80	1.10	1.40	1.70
24*	11.0	-1.0	In computer room at tape drives	0.22	0.32	0.27	0.52
25	13.0	0.5	In computer room at rf power supply	1.85	1.86	1.87	1.67
25*	13.0	0.5	In computer room at rf power supply	1.76	1.78	1.81	1.62
26	13.0	-1.5	In computer room at gradient power supply	1.28	1.24	0.51	0.72
26*	13.0	-1.5	In computer room at gradient power supply	1.03	1.03	0.42	0.67

* Gradient field sequence off.

Table 3.6 Resultant gradient field and time derivative of gradient field at 0.3 m from magnet on patient table as a function of imaging parameters: field-of-view (FOV) and slice thickness (t).

Parameter		Resultant Gradient Field, μT		Resultant Time Derivative, mT/s	
FOV,cm	t,cm	$ B _{\text{rms}}$	$ B _{\text{peak}}$	$ dB/dt _{\text{rms}}$	$ dB/dt _{\text{peak}}$
8	0.3	4.4	10.6	4.0	21
48	0.3	2.6	9.5	3.2	19
48	2.0	2.6	9.6	3.1	20

Table 3.7 Time/location distribution recorded for three persons with TimeWand® bar code system during measurements at OHSU MRI Facility, February 28, 1993. Total elapsed time: 68.16 minutes.

Work area	Person 1 (Joe)		Person 2 (Dan)		Person 3 (Jerzy)	
	mm:ss	Percent	mm:ss	Percent	mm:ss	Percent
Control Room (other areas)	16:00	23.4	31:44	46.7	6:24	9.4
At console	10:56	16.0	0:00	0.0	33:20	49.0
MRI Room (other areas)	5:36	8.2	3:28	5.1	1:52	2.7
At Patient	1:20	2.0	2:08	3.1	1:20	2.0
At Magnet	3:44	5.5	3:28	5.1	1:36	2.4
Computer Room	0:00	0.0	0:32	0.8	0:32	0.8
Other Rooms	30:40	44.9	26:40	39.2	22:56	33.7
Total	68:16	100.0	68:00	100.0	68:00	100.0

Figure 3.1: Static magnetic field measurements in millitesla (mT) at height of 1.1 m in the vicinity of MRI magnet.

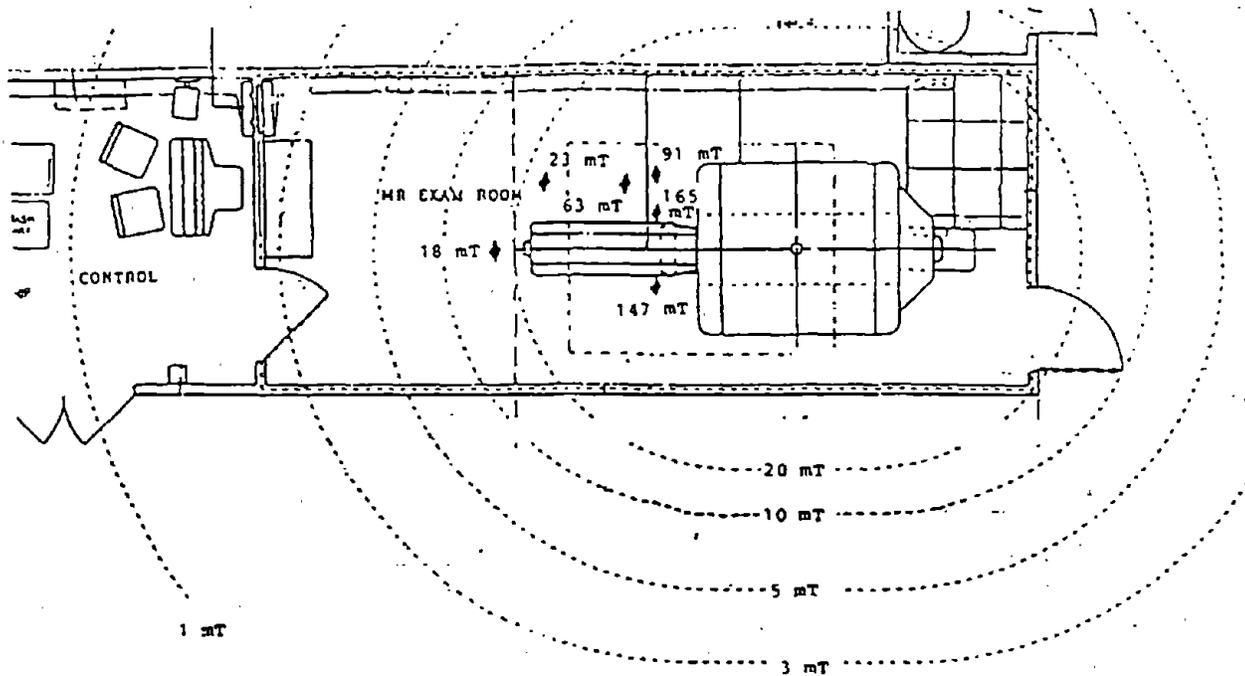


Figure 3.2: Component and resultant gradient field waveforms at four heights recorded 0.5 m in front of magnet and 0.5 m off axis (Location 03): a) Height, 0.8 m; b) Height, 1.1 m; c) Height, 1.4 m; and d) Height, 1.7 m.

a) Height, 0.8 m

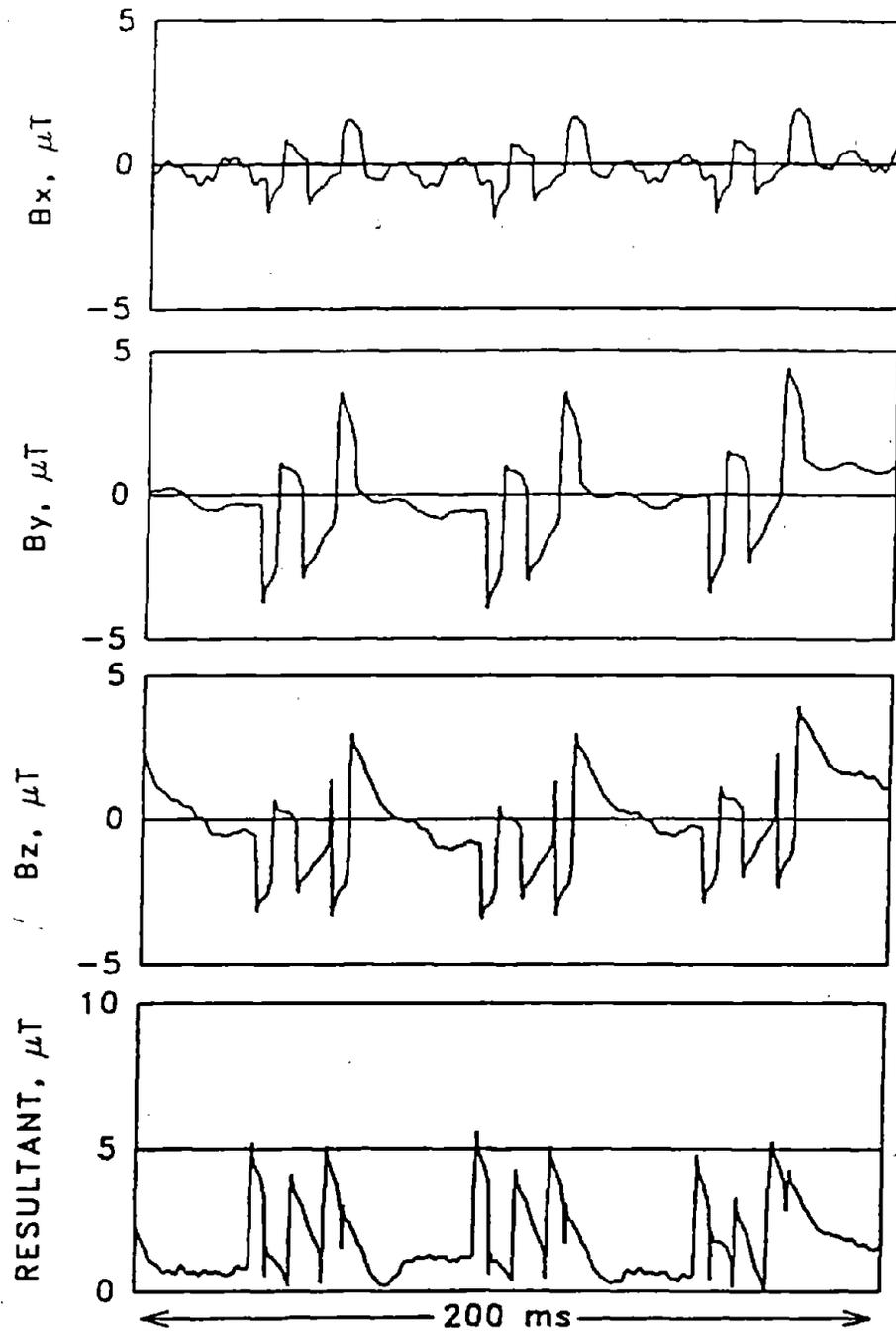


Figure 3.2, continued

b) Height, 1.1 m

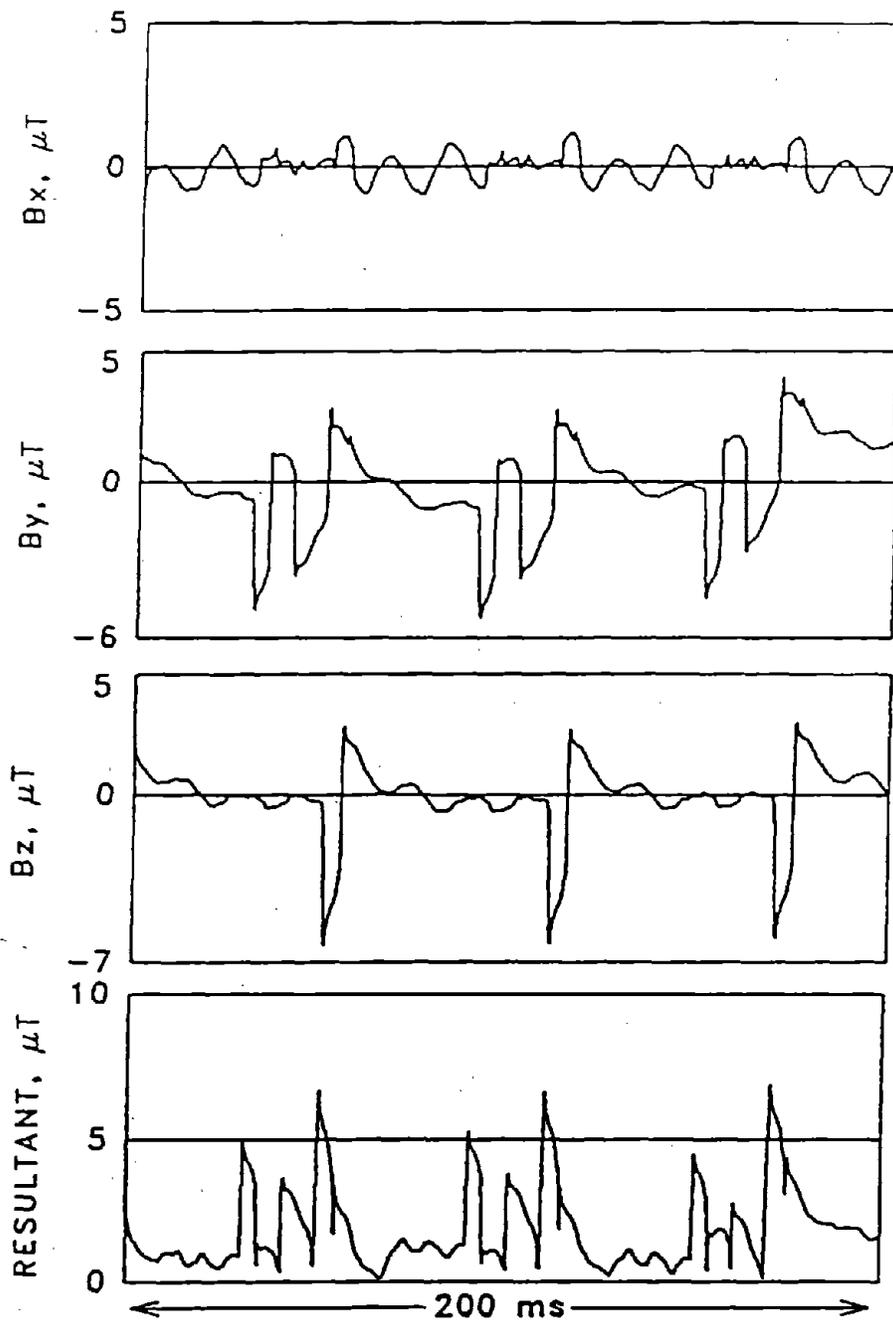


Figure 3.2, continued

c) Height, 1.4 m

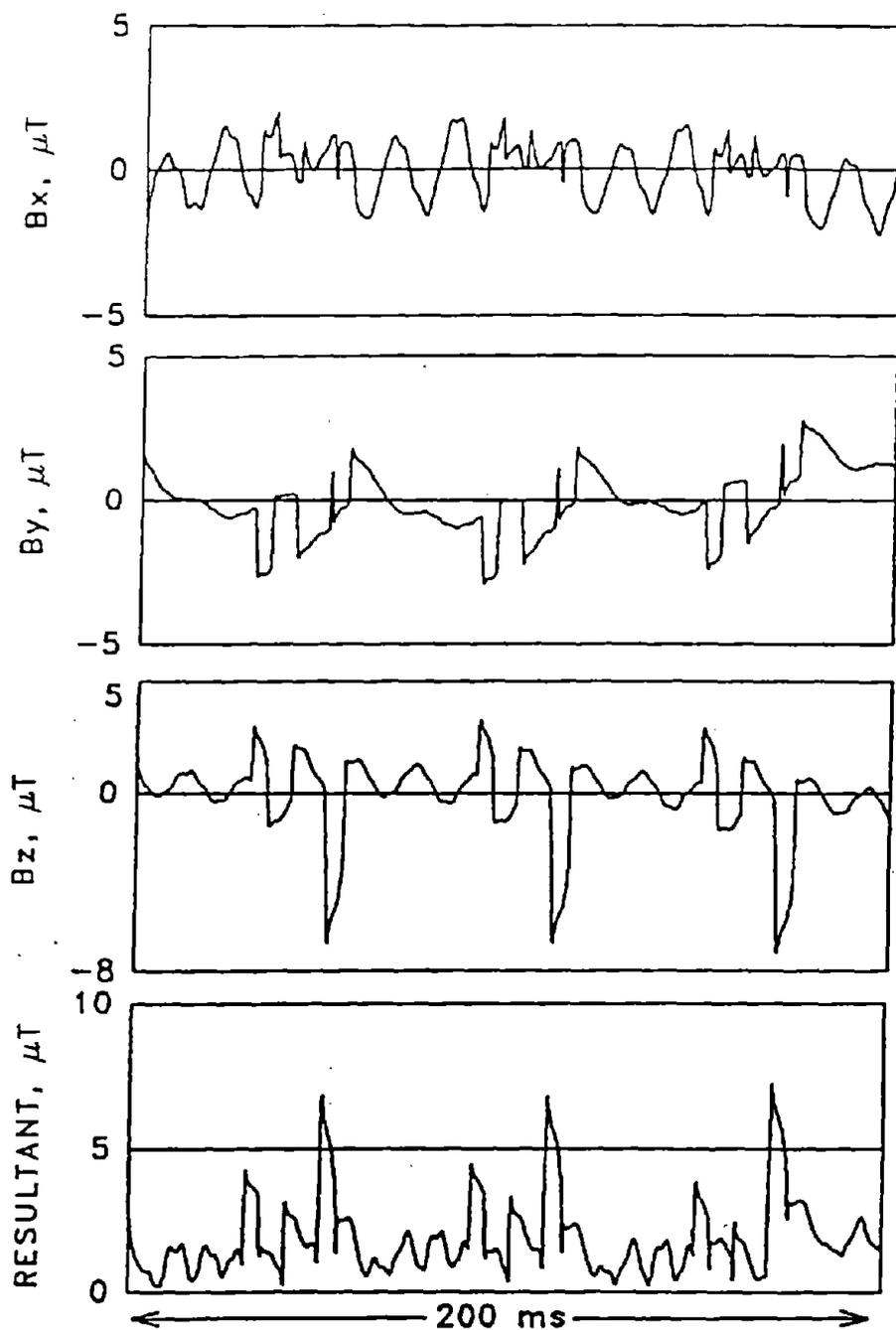


Figure 3.2, continued

d) Height, 1.7 m.

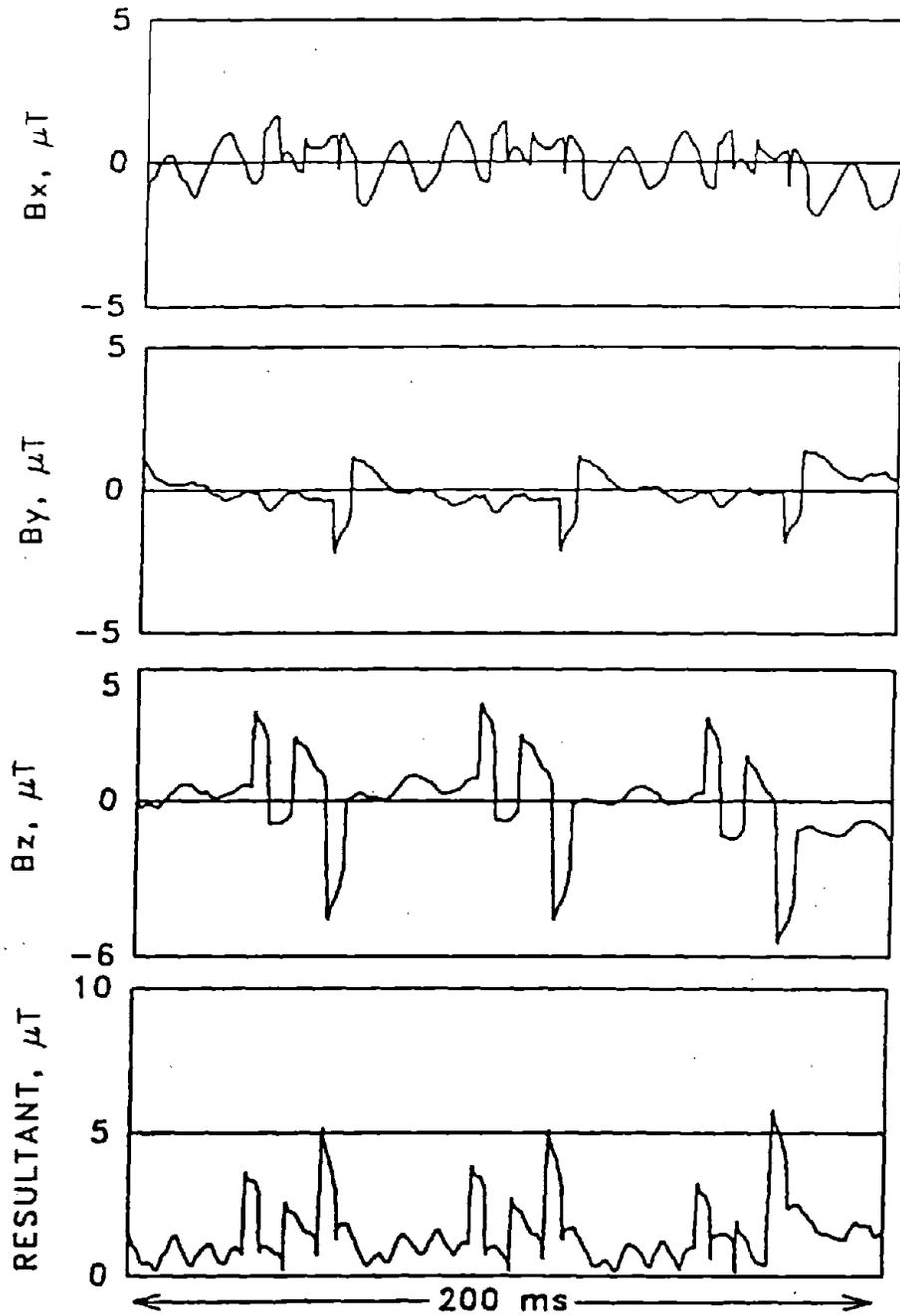
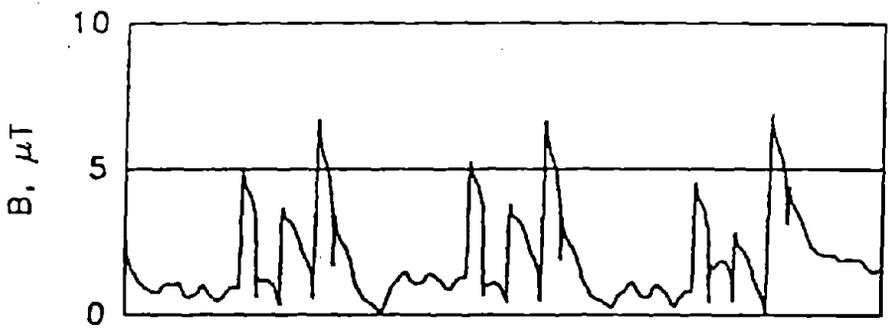


Figure 3.3: Resultant gradient field waveforms at four heights recorded at 0.5 m in front of magnet and 0.5 m off axis (Location 03): a) Height 0.8 m; b) Height 1.1 m; c) Height 1.4 m; and Height 1.7 m.

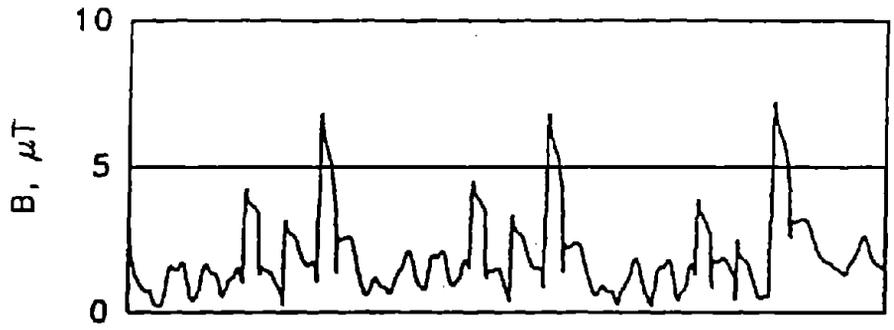
a) Height, 0.8 m



b) Height, 1.1 m



c) Height, 1.4 m



d) Height, 1.7 m

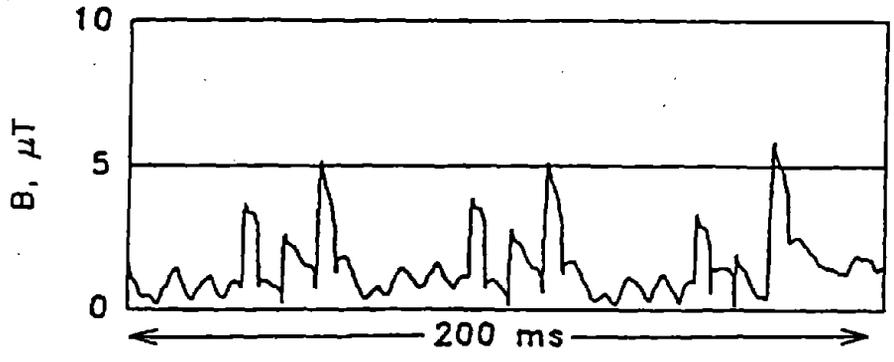
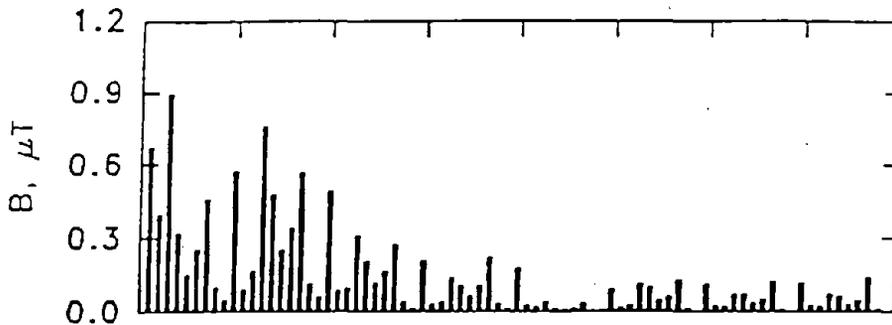
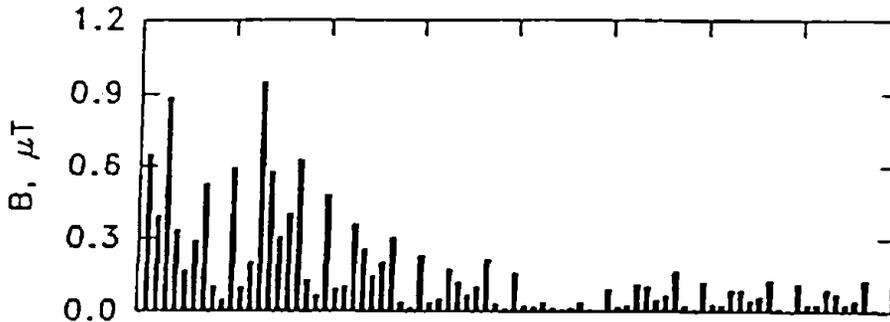


Figure 3.4: Frequency spectra (5-400 Hz) of resultant gradient field waveforms at four heights recorded at 0.5 m in front of magnet and 0.5 m off axis (Location 03): a) Height 0.8 m; b) Height 1.1 m; c) Height 1.4 m; and Height 1.7 m.

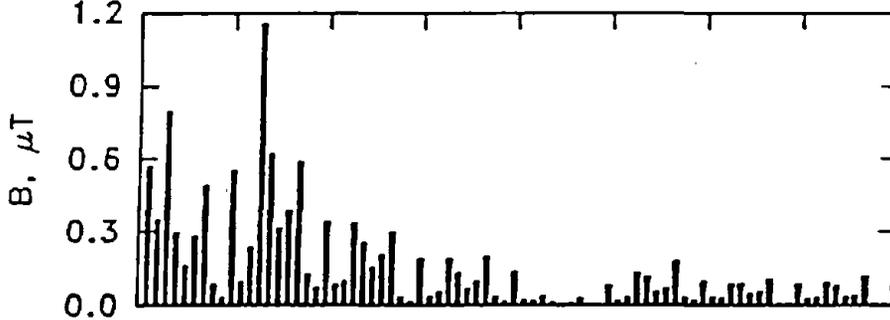
a) Height, 0.8 m



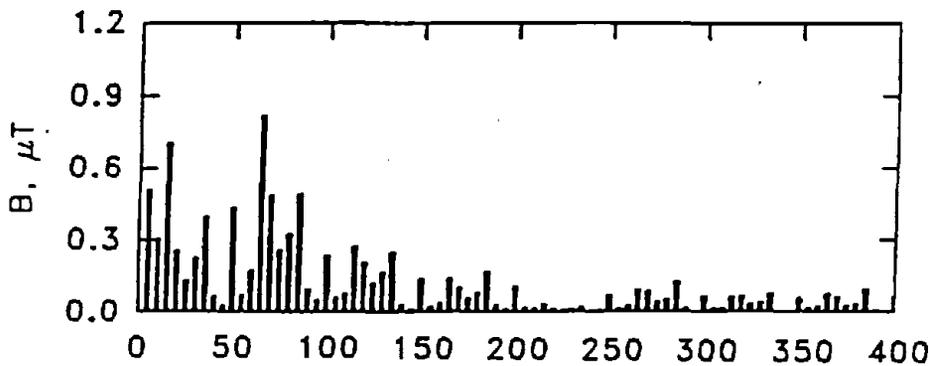
b) Height, 1.1 m



c) Height, 1.4 m



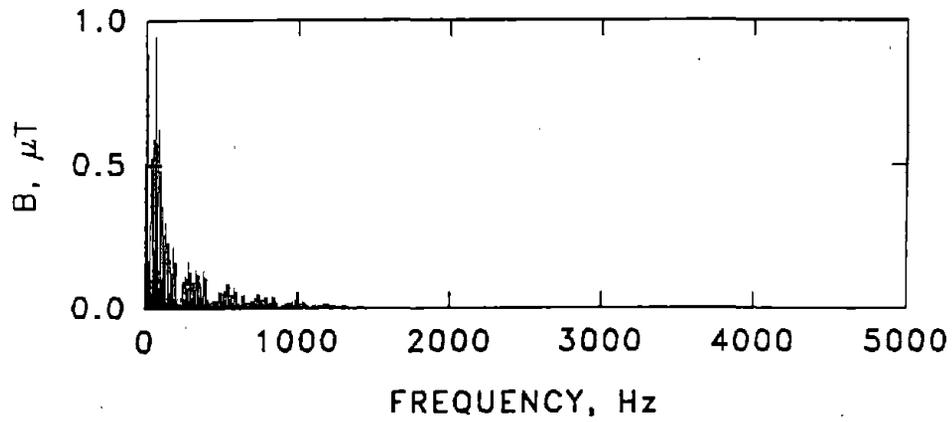
d) Height, 1.7 m



FREQUENCY, Hz

Figure 3.5: Frequency spectrum (5-5000 Hz) for gradient field at 1.1 m height at 0.5 m from magnet face and 0.5 m from magnet axis (Location 03): a) 5-5000 Hz; and b) 1000-5000 Hz.

a) 5-5000 Hz



b) 1000-5000 Hz

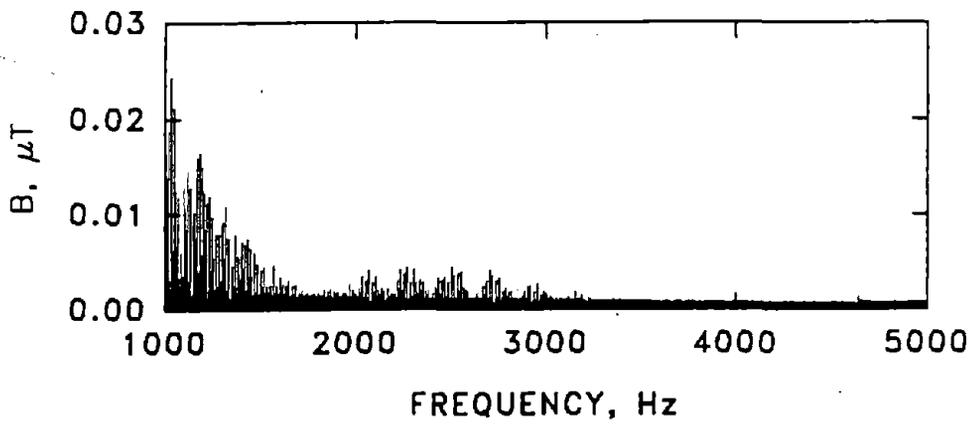
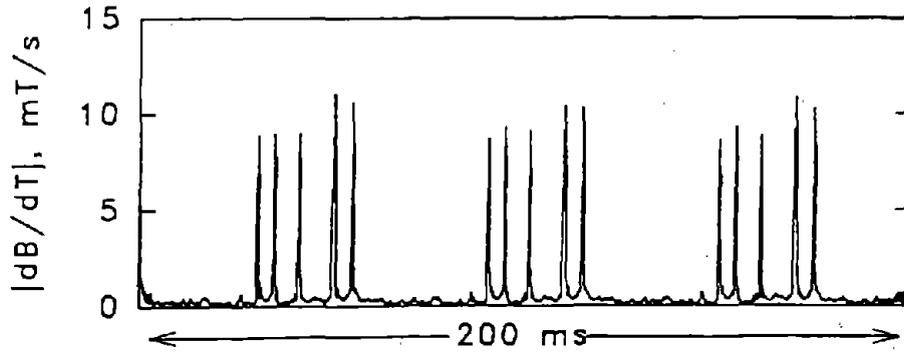
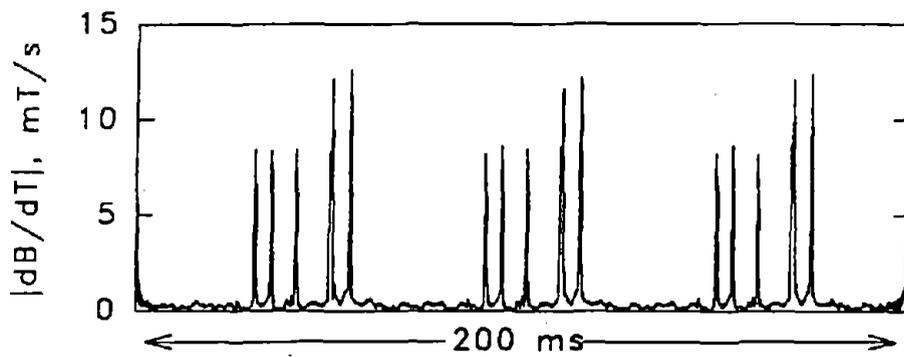


Figure 3.6: Waveforms of the magnitude of the gradient field time derivative ($|dB/dt|$) at four heights at 0.5 m in front of magnet and 0.5 m off axis (Location 03): a) Height 0.8 m, b) Height 1.1 m; c) Height 1.4 m; and d) Height 1.7 m.

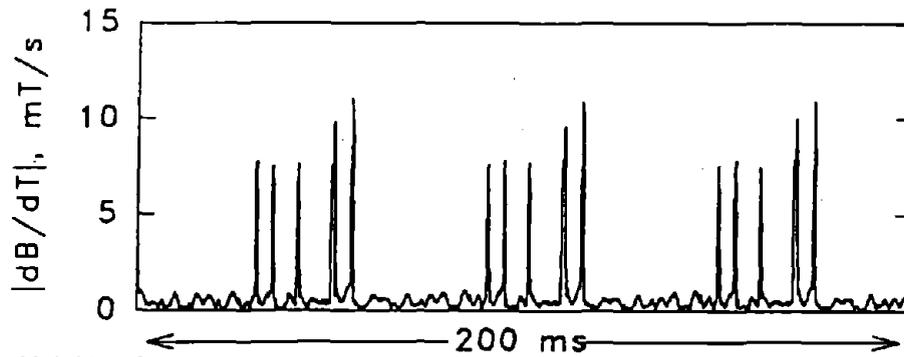
a) Height, 0.8 m



b) Height, 1.1 m



c) Height, 1.4 m



d) Height, 1.7 m

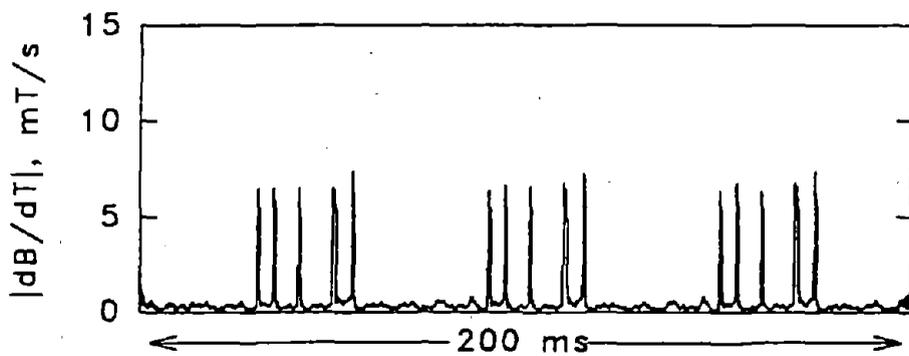
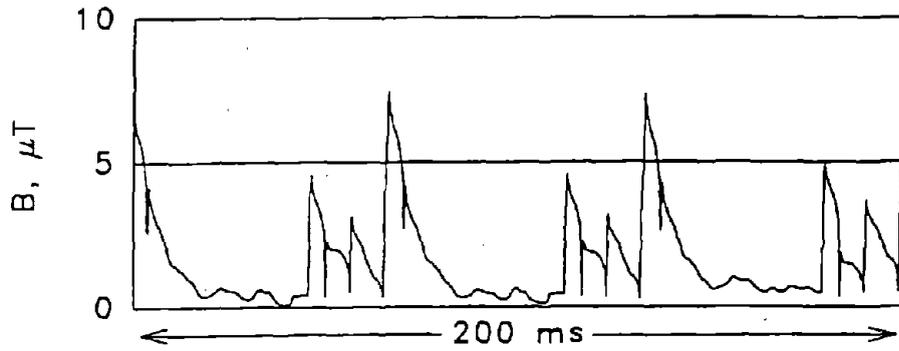
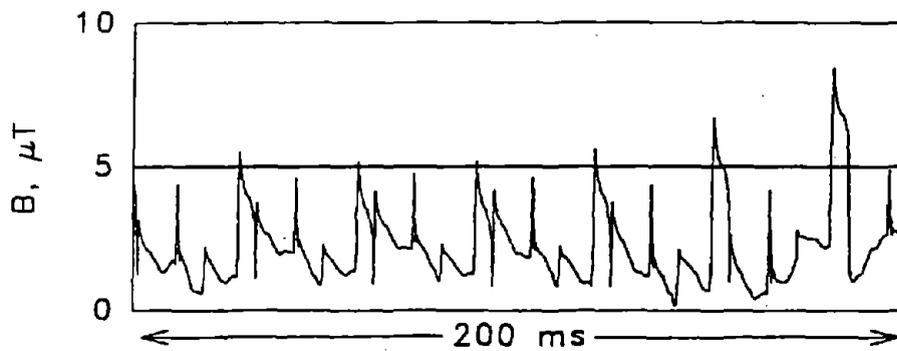


Figure 3.7: Effect of gradient field attenuation on resultant field waveforms recorded at 0.5 m in front of magnet and 0.5 m off axis (Location O3) at a height of 1.1 m: a) Maximum gradient field; b) One-half maximum gradient field ; and c) One-quarter maximum gradient field.

a) Maximum gradient field



b) One-half maximum gradient field



c) One-quarter maximum gradient field

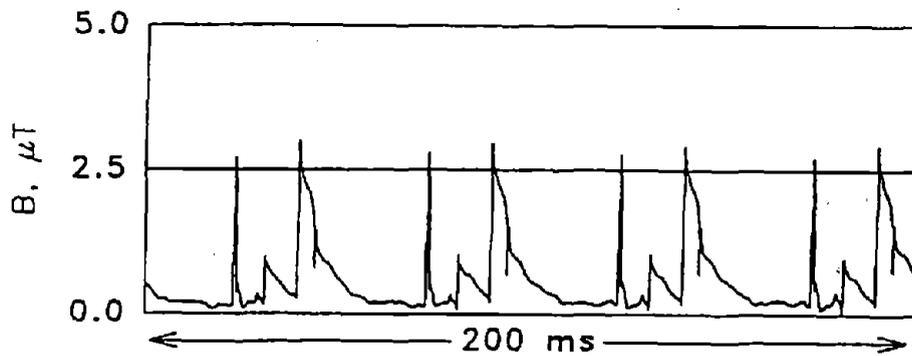
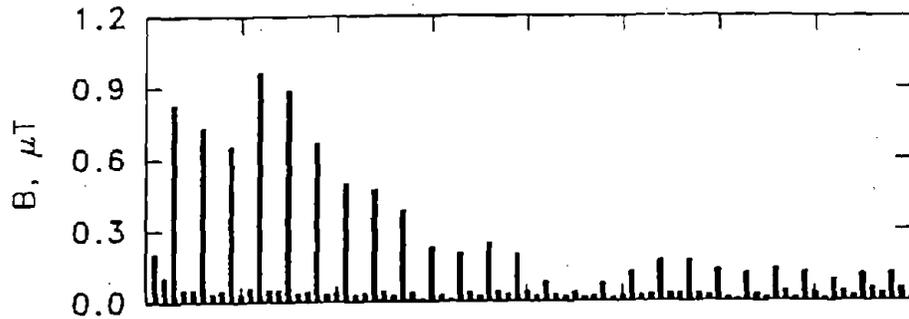
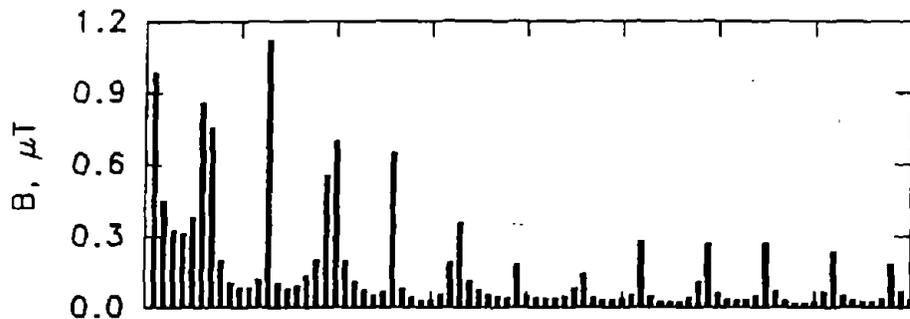


Figure 3.8: Effect of gradient field attenuation on resultant field frequency spectra (5-400 Hz) recorded at 0.5 m in front of magnet and 0.5 m off axis (Location 03) at a height of 1.1 m: a) Maximum gradient field; b) One-half maximum gradient field ; and c) One-quarter maximum gradient field.

a) Maximum gradient field



b) One-half maximum gradient field



c) One-quarter maximum gradient field

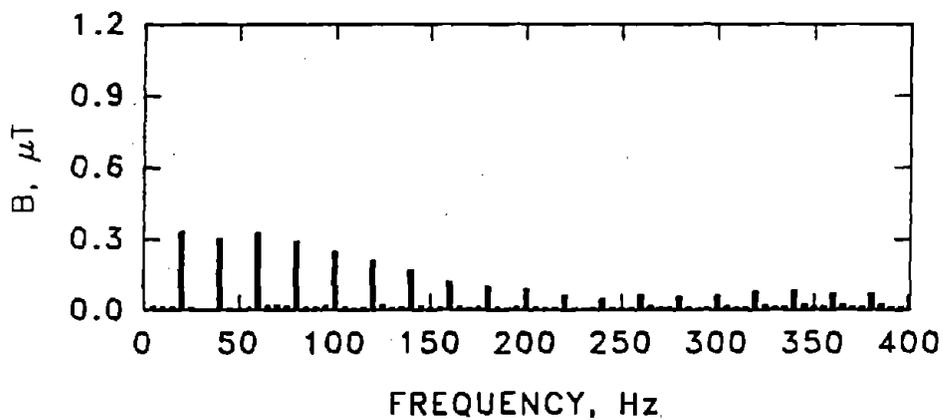
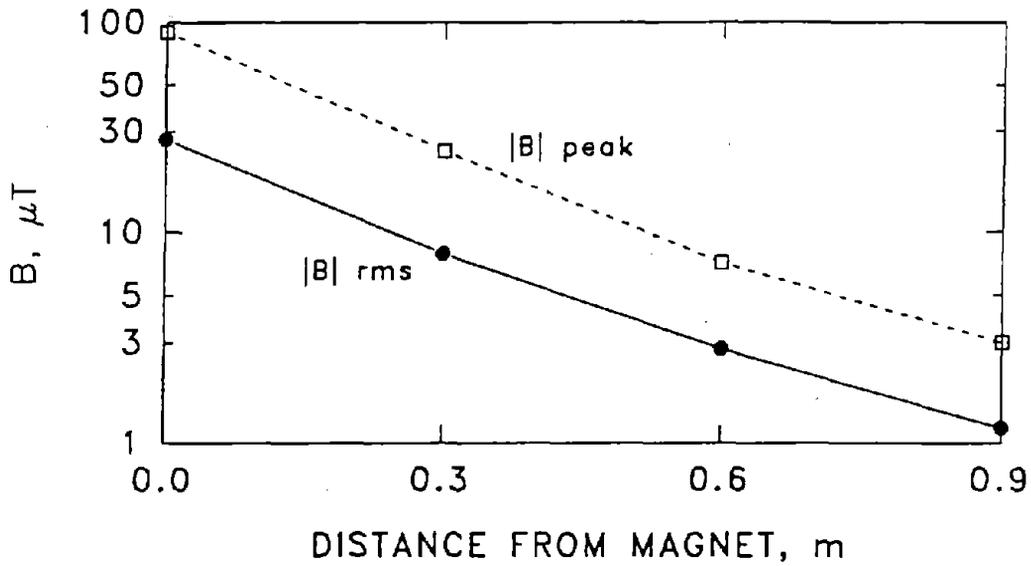


Figure 3.9: Horizontal profiles along the patient table for: a) resultant gradient field; and b) time derivative of gradient field.

a) Resultant gradient field



b) Time derivative of gradient field

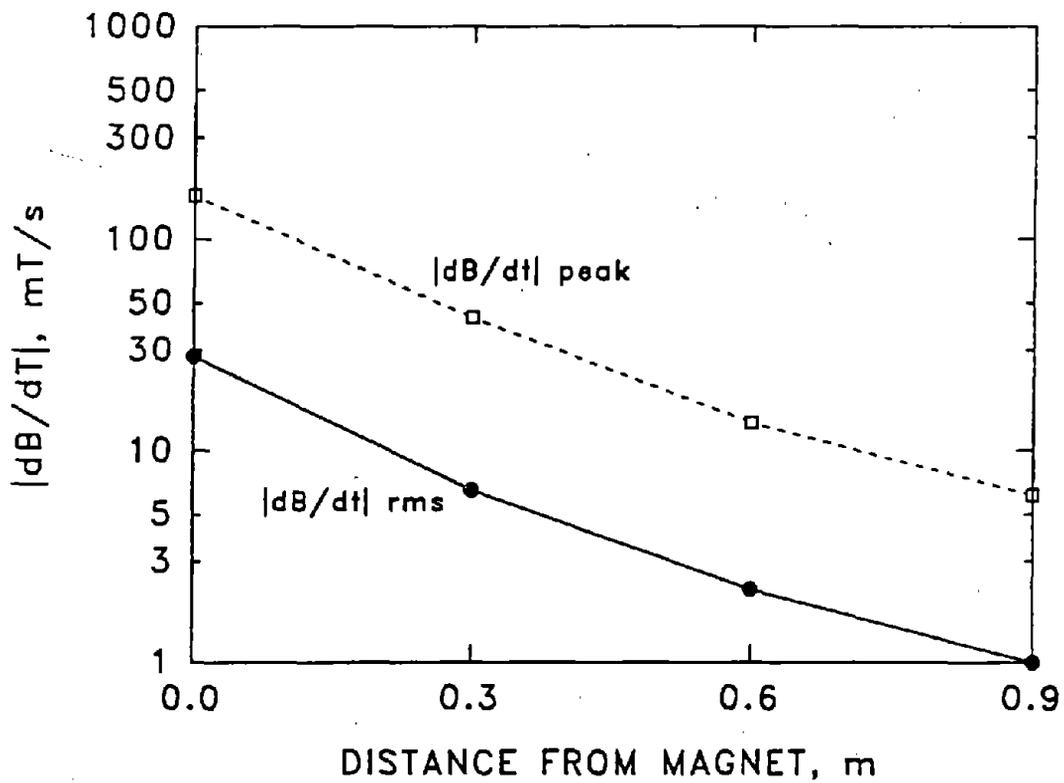


Figure 3.10: Resultant gradient field waveforms as a function of distance from magnet along the patient table: a) 0.0 m; b) 0.3 m; c) 0.6 m; and d) 0.9 m.

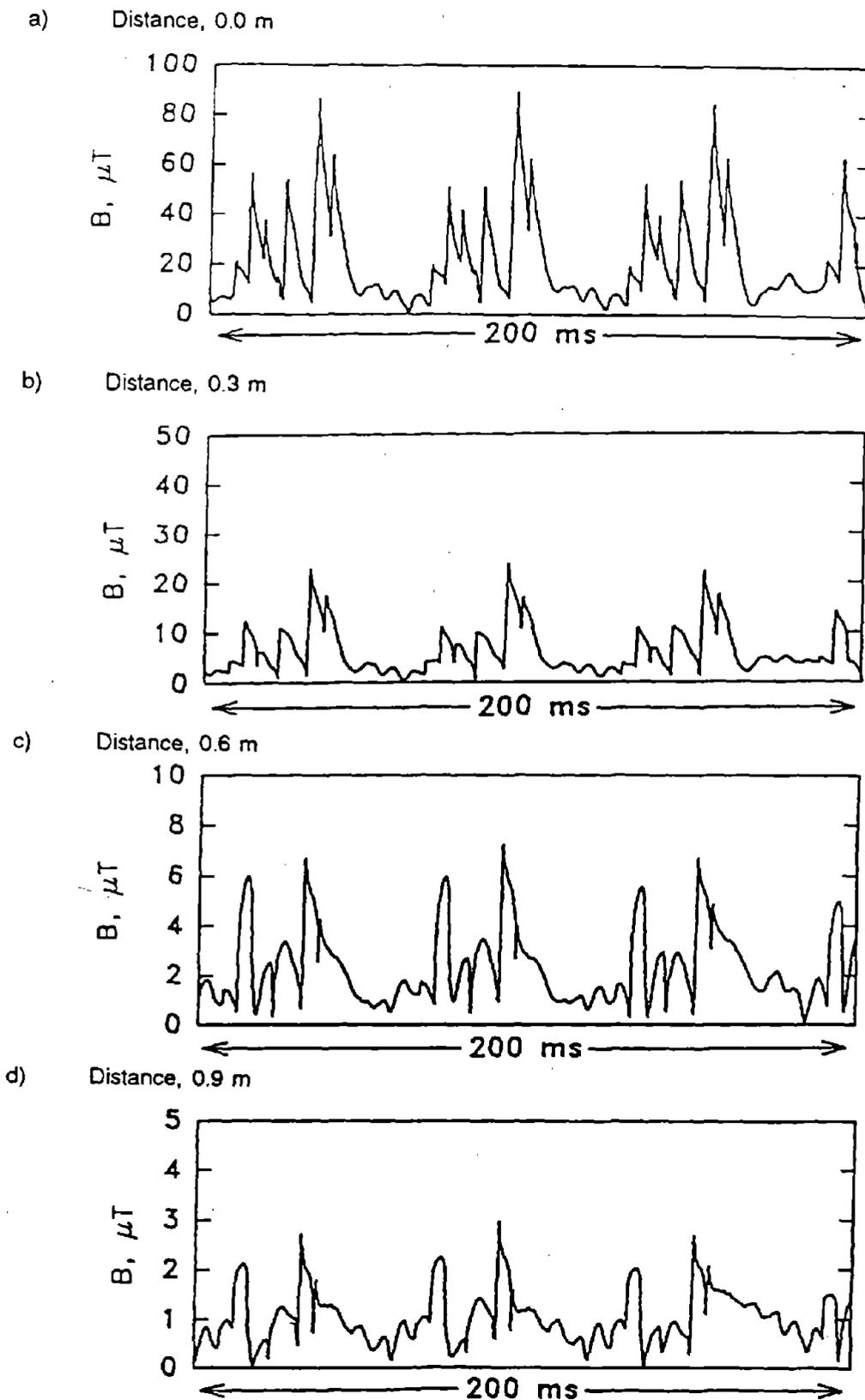


Figure 3.11: Resultant gradient field frequency spectra (5-400 Hz) as a function of distance from the magnet along the patient table: a) 0.0 m; b) 0.3 m; c) 0.6 m; and d) 0.9 m.

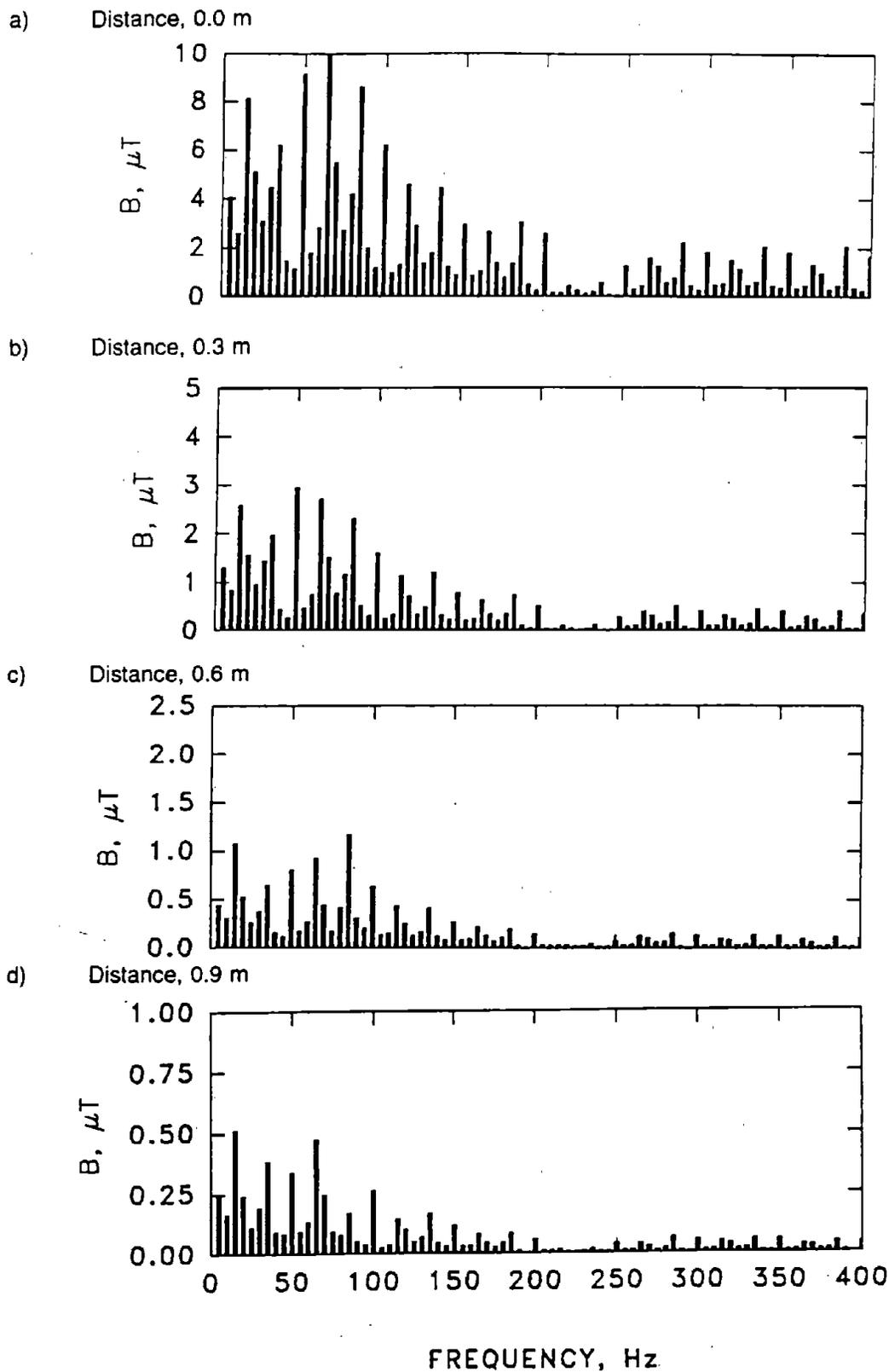


Figure 3.12 Waveforms of magnitude of gradient field time derivative ($|dB/dt|$) as a function of distance from the magnet along the patient table: a) 0.0 m; b) 0.3 m; c) 0.6 m; and d) 0.9 m.

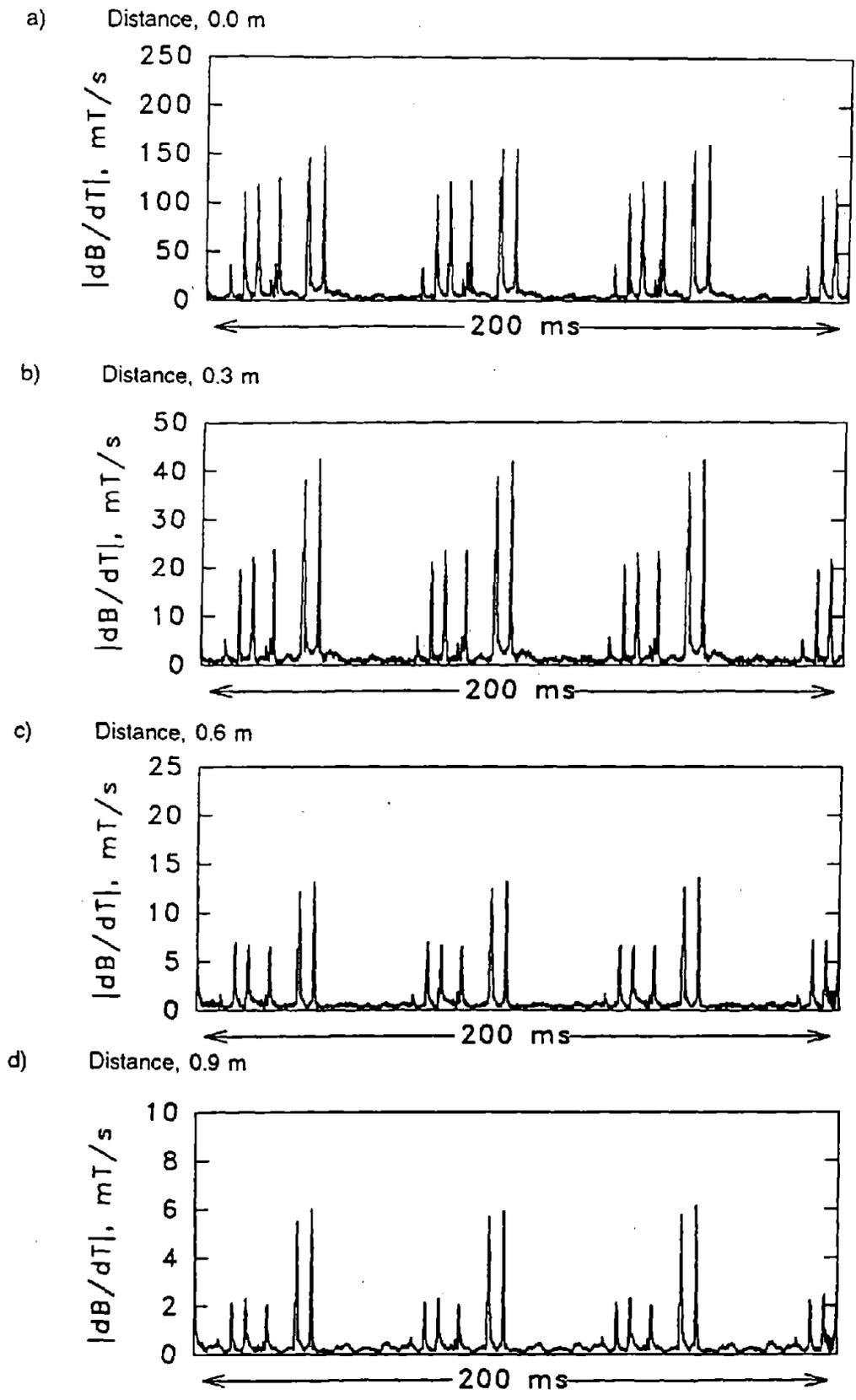


Figure 3.13 Average rms gradient field level contours in microtesla at height of 1.1 m near MRI magnet.

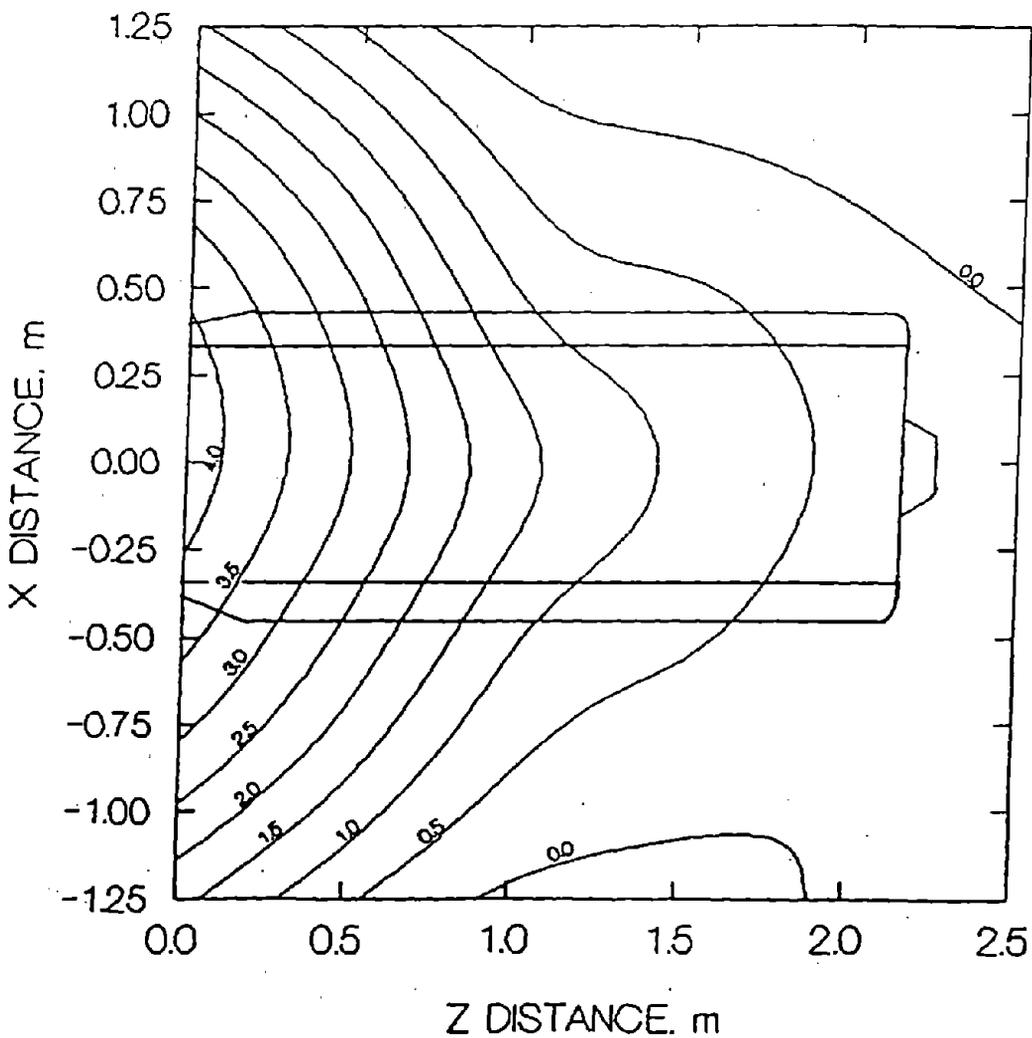


Figure 3.14: Resultant gradient field in microtesla (μT) as a function of distance along the patient table for different pulse sequence parameters.

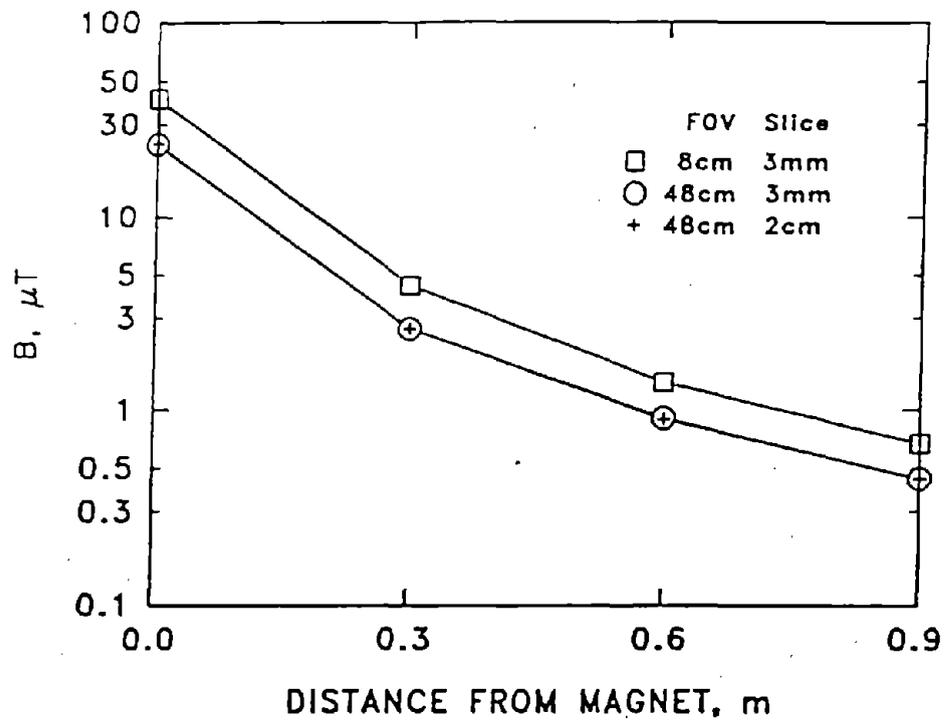
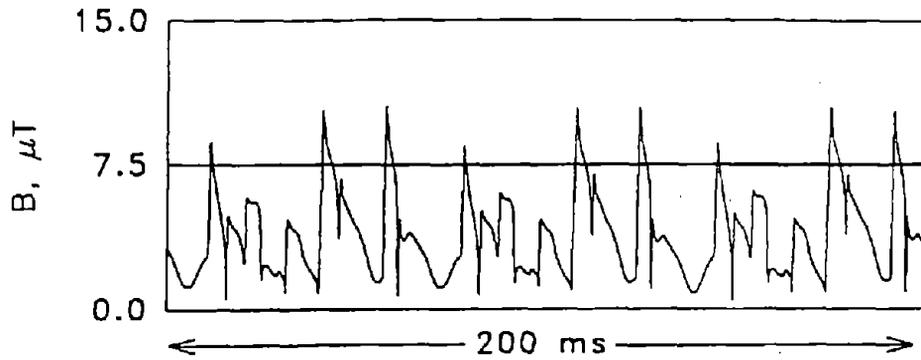
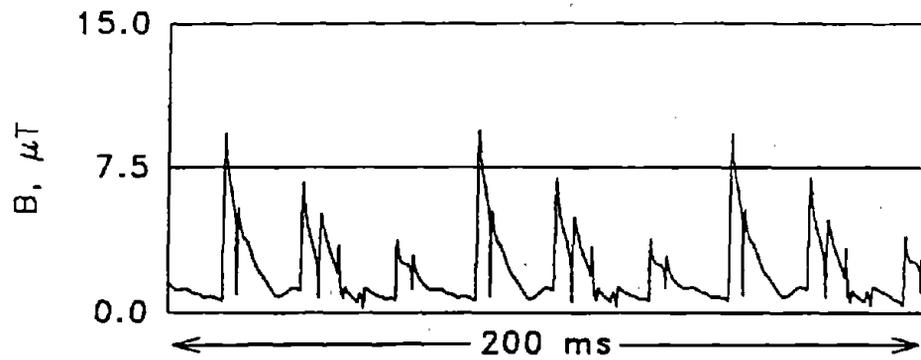


Figure 3.15: Effect of gradient pulse sequence parameters, field-of-view (FOV) and slice thickness (t), on resultant gradient field waveforms measured at 0.3 m from magnet on patient table: a) FOV = 8 cm, t = 3 mm; b) FOV = 48 cm, t = 3 mm; and c) FOV = 48 cm, t = 2 cm.

a) FOV = 8 cm, t = 3 mm



b) FOV = 48 cm, t = 3 mm



c) FOV = 48 cm, t = 2 cm

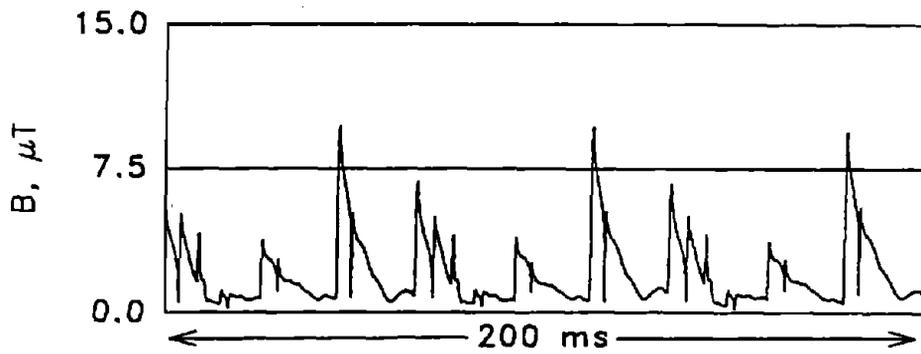
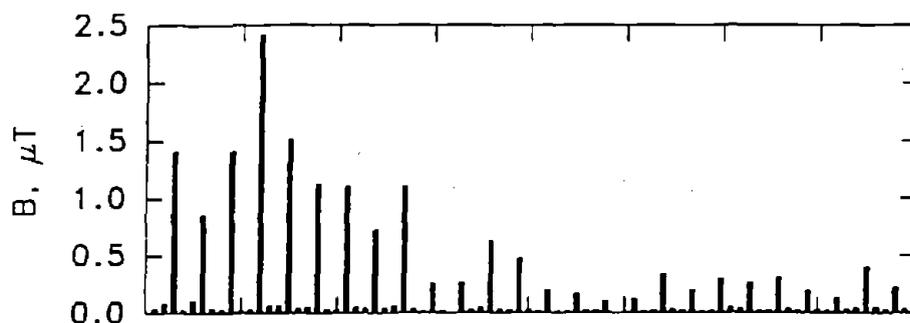
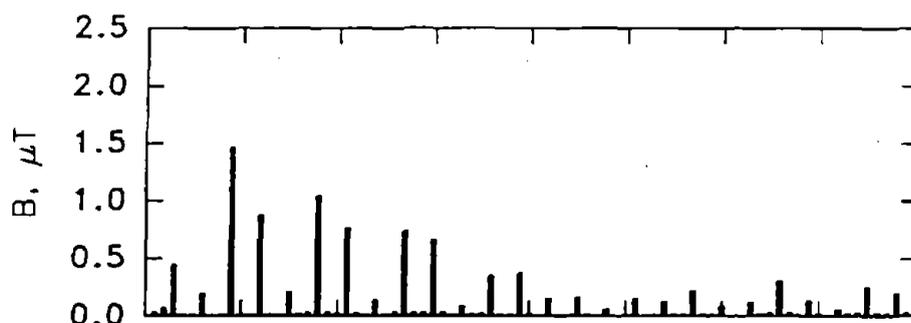


Figure 3.16: Effect of gradient pulse sequence parameters, field-of-view (FOV) and slice thickness (t), on resultant gradient field frequency spectra (5-400 Hz) measured at 0.3 m from magnet on patient table: a) FOV = 8 cm, t = 3 mm; b) FOV = 48 cm, t = 3 mm; and c) FOV = 48 cm, t = 2 cm.

a) FOV = 8 cm, t = 3 mm



b) FOV = 48 cm, t = 3 mm



c) FOV = 48 cm, t = 2 cm

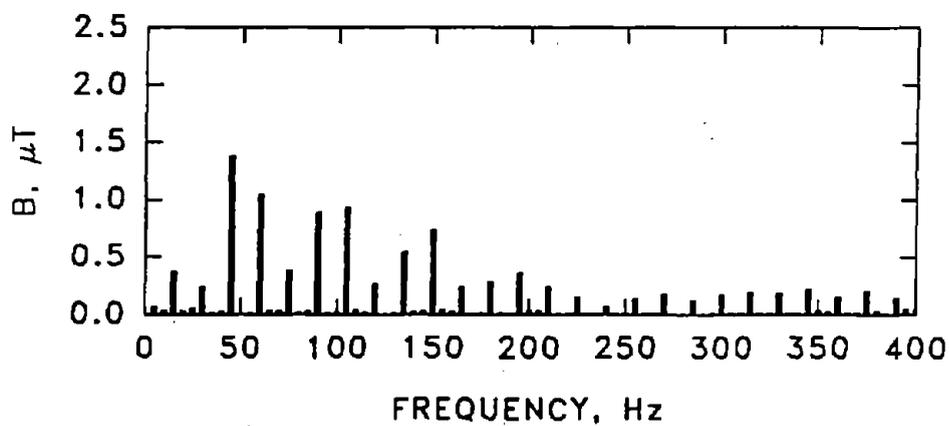
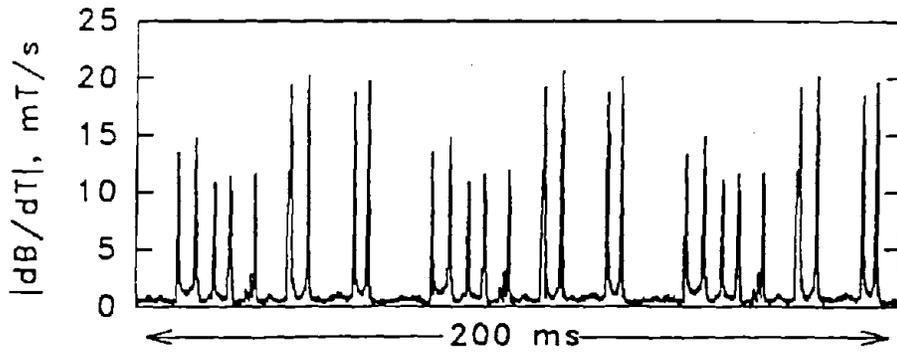
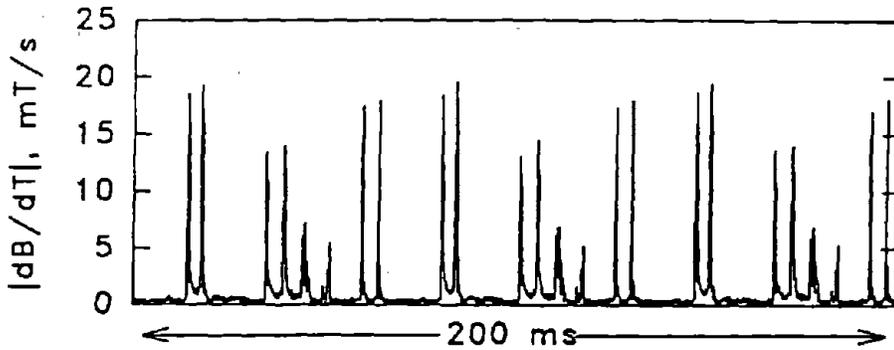


Figure 3.17: Effect of gradient pulse sequence parameters, field-of-view (FOV) and slice thickness (t), on gradient field time derivative ($|dB/dt|$) measured at 0.3 m from magnet on patient table: a) FOV = 8 cm, t = 3 mm; b) FOV = 48 cm, t = 3 mm; and c) FOV = 48 cm, t = 2 cm.

a) FOV = 8 cm; t = 3 mm



b) FOV = 48 cm; t = 3 mm



c) FOV = 48 cm; t = 2 cm

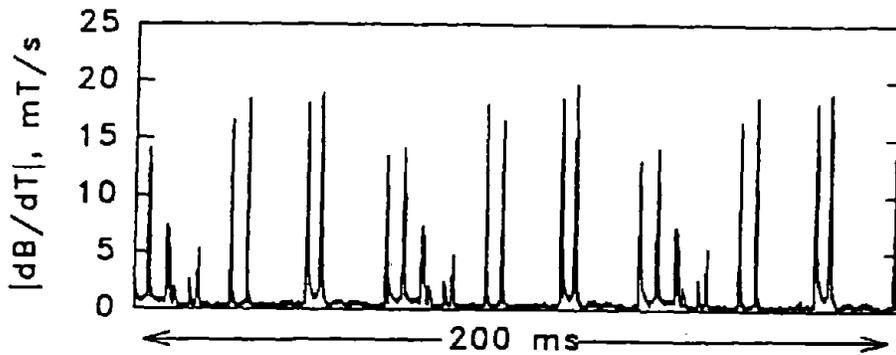


Figure 3.18 Manually recorded time/location data for one individual during measurements at OHSU MRI facility, February 28, 1993. Total elapsed time: 1080 seconds (18 minutes)

Digital clock

07:13:30

02/28/93
Date: mm/dd/yy

Location Key: M: At magnet L: In control room
P: At patient C: Computer Room
X: In exam room O: Other rooms
N: At console

Facility: OHSU MRI Facility
Measurement Procedure
Evaluation

—Technologist 1—		Technologist 2—		Other 3	
Name: Joe		Name: Joe, cont.		Name:	
Time	Work area	Time	Work area	Time	Work area
14:55	X	15:10:08	L		
14:55	O	11:00	X		
14:56	L	11:23	L		
14:57	X	11:38	X		
14:58	O	12:00	L		
14:59	L	12:22	O		
15:00:00	X	12:31	L		
00:23	L	15:12:50	O		
03:34	X				
04:04	L				
04:32	O				
66:29	L				
07:56	X				
15:08:02	L				

Instructions:

- Enter the time a new work area is entered.
- Enter time to the nearest 10 seconds if possible.
- Do not enter durations of less than 10 seconds.
- If an entry is omitted enter an approximate time and the work area followed by an A.

4.0 Discussion

4.1 Static Field

The static field measurements agreed with the field contours provided on the site drawing by the manufacturer of the MRI system. The static field magnitudes varied by 10 to 20 percent over body heights at particular measurement locations. These results indicate that the static field levels in the plane of the magnet axis provided by the manufacturer should be sufficient to estimate exposures. If this approach is taken, it will be necessary to obtain more detailed magnetic field contour maps for a facility than that obtained for the OHSU facility. The static fields for a particular MRI system will be the same for different installations in work areas near the magnet, thus standardizing exposure levels to some extent. Shielding at a facility could change field levels in remote work areas.

Examination of the measured static fields allowed estimates of the static fields in the various work areas for the purposes of computing exposures. Ranges of static fields and a representative field value for exposure purposes for each work area are given in Table 4.1. The values for static field in Table 4.1 range over three orders of magnitude with levels at the magnet being considerably higher than elsewhere. This indicates the need to accurately estimate time spent in the two work areas near the magnet.

The small dosimeter appeared to measure static fields with sufficient accuracy for exposure measurements in the high fields near the magnet and patient table. However, given the wide range of fields and the short times spent in high fields, the time-weighted average exposure that is accumulated by the meter does not capture certain important characteristics of this type of exposure: namely the maximum field and time spent in the highest fields. Therefore the use of the dosimeter as presently configured would best be accompanied by recording the time spent in various work areas, particularly in the "at the magnet" and "at the patient" areas.

4.2 Gradient Fields

The magnitudes of the gradient field, $|B|$, and time derivative, $|dB/dt|$, decreased rapidly as distance from the magnet was increased. At a distance of one meter, field magnitude dropped to that of localized power frequency sources ($<1\mu T$). Similar attenuation with distance was noted for the rms fields in the VLF and LF ranges. The rapid decrease with distance for all these gradient field related parameters suggests that gradient field exposures are only significant in the work area at the magnet and, there, only when MRI imaging is taking place. Furthermore, the MRI technicians are generally not in the MRI room when the gradient fields are operating. There is no exposure to gradient fields in the control room. In much of the facility, magnetic field exposures associated with the 60 Hz power supply system predominate in the ELF range.

At most locations, the waveforms and component magnitudes changed with height, but for the most part gradient field magnitudes were fairly constant over height ($\pm 20\%$). The lowest fields at a location were at head height (1.7 m) and the highest fields were at chest height (1.4 m). In general, it appears that one or two sensors for gradient fields should be sufficient for characterization. However, the use of four sensors oriented horizontally expedited measurement of lateral profiles along the patient table.

The very localized nature of the gradient fields suggests that their characterization at a site for the purposes of exposure assessment can be done with a few measurements at the face of the magnet. The Multiwave™ System demonstrated its capability to perform such a characterization quickly. The problems with RF shielding, frequency response and triggering that were encountered, should be corrected prior to additional measurements.

A single or multiple sensor instrument mounted on a mobile platform and triggered to record fields at specified distance intervals is frequently employed to produce lateral profiles and field contour maps especially near electric transmission line facilities. Application of such an instrument for field characterization in the MRI environment may also be appropriate because it provides a method of rapidly acquiring field data that can be easily displayed in graphical form.

Near the magnet, triggered samples would have to be taken at closely spaced intervals to capture the spatial variation of the fields, especially the gradient fields. The sensor would have to be detachable from the wheeled platform to allow measurements in obstructed locations such as over the patient table. For static fields, the use of a triggered recording instrument would offer considerable advantage over point-by-point measurements, since levels of this parameter are of interest throughout a facility. In addition, the static fields lend themselves to a single point-in-time measurement that can be accommodated by a triggered instrument that is being moved. However, the use of manufacturers' field contours, if available, is probably a more efficient method of characterizing the static field in a facility.

As noted above, relatively few measurements would be needed to characterize gradient field levels. These measurements would be near the magnet where the use of a wheeled device would be impaired by the patient table. Furthermore, the low frequency pulsed nature of the gradient fields requires a longer sampling period for averaging or to capture a useful waveform (200 ms was used in the pilot study). This may impose constraints on the speed with which the instrument could be moved and dictate more than a single broadband measurement of field magnitude. Therefore, the use of this approach for gradient field field measurements would not have the advantage it would for static field measurements. On the other hand, if characterization of broadband fields in the ELF or other ranges is needed throughout a facility, an instrument with the capability to automatically record field measurements as a function of location would be highly desirable.

Ideally, the signal processing and recording functions of whatever instrument is used would be integrated with the sensor. However, immunity of the instrument from static and RF fields would have to be verified before it could be used in the MRI environment. If interference is a problem, then long cables to the sensor would have to be employed, as was done in this pilot study. Obviously, the application of existing distance-triggered instrumentation, say for power frequency fields, would require testing of its compatibility in the MRI environment as well as its suitability for characterizing gradient fields. Thus, the use of a profiling instrument for characterizing fields in the MRI environment merits further investigation.

For the purposes of exposure assessment, the ranges and a representative value of the gradient field in each work area with the MRI system operating have been listed in Table 4.1. In many cases, the representative values were associated with power frequency fields in the work area rather than with gradient fields from the MRI imaging process. Although the overall range of values was not as great as for static fields, it was still clear that the area where highest exposures occurred was at the magnet. Thus, for gradient field exposure assessment, just as for static fields, knowledge of time spent adjacent to the magnet is crucial.

4.3 Radio Frequency Fields

The broadband survey meter was not suitable for characterizing the RF signals near the MRI system. Clearly, there were RF fields present, as evidenced by the interference to the induction coil preamplifiers. As with the lower frequency fields, it appears that RF fields attenuate quickly as distance from the magnet increases. Thus, for exposure assessment purposes, the important work zone in which to quantify RF field level and time spent is the area adjacent to the magnet.

The low, but undetectable, levels of RF fields in work areas suggest that more appropriate instrumentation be used to quantify levels. A tunable RF signal analyzer with waveform storage capability would seem most appropriate.

4.4 Time and Location Monitoring

The localized nature of extreme field levels emphasize the need to accurately quantify time spent in work areas near the magnet. For estimates of exposure, uncertainty in the estimate of time spent near the magnet could easily overshadow the uncertainty in the field assigned to that work location. Either of the two methods of recording time and location tested here could be used for normal technician activities which are not as frenetic as those during measurements.

The manual method offers simplicity and the possibility of self reporting. If the number of work zones of interest can be reduced to two or three, then a manually kept log of time spent near the magnet during a day would be a feasible method for obtaining extensive data from many sites.

The TimeWand® barcode system is advantageous for monitoring several individuals and work zones. However, it requires the presence of an observer. The system is therefore best suited for intensive investigations of time spent in locations as a function of image protocols and site-specific procedures. TimeWand® data could also be useful in developing and verifying the self-reporting manual log.

Estimates of the time-integrated static and gradient exposure experienced by Dr. Joe Bowman during the period of TimeWand® time/location monitoring on February 28, 1993 are presented in Table 4.2. For static fields, about 75% of the time weighted exposure was accumulated in the 5.5% of time spent at the magnet. The time-weighted average (TWA) static field during this hour was about 11 mT, twice the value recorded by the small dosimeter over the five hour period it was worn. This difference in TWA fields is not surprising given their dependence on time spent adjacent to the magnet, which would have varied considerably during the course of the day in the MRI facility.

The gradient field exposures were also dominated by the 5.5% of time spent near the magnet. In this case, that time contributed an estimated 50% of total exposure. The TWA gradient field for the 68 minutes of observation was 0.2 μ T. The gradient fields were on for essentially the entire time of time/location monitoring. To apply this technique to practical situations, knowledge of whether the gradient fields were on or not would be required.

This example of exposure estimating, even if only for a short time, again emphasizes the need to accurately estimate the time spent in the work area near the magnet. Similar estimates over the course of a day for technicians at a few facilities could provide guidance in the design of exposure assessment protocols. For example, estimates of between-facility and between-procedure variation in time spent in particular work areas could be produced by such measurements.

Samples of two facility activity logs were obtained from the MRI operator to assess them as a source of operator activity. The patient and activity logs record minimal information about each patient and procedure: viz., type of scan, time, name and study number. In the interests of anonymity, dates and patient names have been excised in the sample pages shown in Figure 4.1. These or similar logs may provide a means of estimating the number, type and duration of MRI imaging protocols performed at a facility for a representative period of time. Time/location observations could then be made for the most prevalent procedures to yield average time in work areas for a single procedure. The integrated time over a month could then be estimated from the frequency of performance data. It may also be possible to obtain data on facility activity from the memory of an MRI computer, if appropriate software is available from the MRI manufacturer.

Table 4.1: Estimated magnetic fields in work areas for the purpose of exposure estimates. Gradient field levels represent periods when the MRI system is on.

Work Area	Static field, mT		Gradient field, μ T	
	Range	Representative value	Range	Representative value
Control room	1-3	2	0.09-0.14	0.1
At console	1.5	1.5	0.05-0.08	0.07
MRI room	3-30	15	0.03-0.1	0.05
At the patient	20-60	40	0.2-1.2	0.5
At the magnet	90-160	150	1.0-2.5	2.0
Computer room	0.2-0.8	0.5	0.2-1.8	0.5
Other rooms	0.2-3	0.5	0.04-0.2	0.1

Table 4.2 Estimated time integrated static and gradient magnetic field exposures for one investigator during TimeWand® time/location observations at OHSU MRI facility on February 28, 1993. Total elapsed time: 1.13 hours (68 minutes). Gradient fields assumed to be on during period of observation.

Location	Time, h	Static field		Gradient field	
		Field, mT	Exposure, mT-h	Field, μ T	Exposure, μ T-h
Control room	0.26	2.0	0.52	0.1	0.026
At console	0.18	1.5	0.24	0.07	0.013
MRI room	0.093	15	1.40	0.05	0.005
At patient	0.022	40	0.88	0.5	0.011
At magnet	0.062	150	9.30	2.0	0.124
Computer room	0.0	0.5	0.0	0.5	0.0
Other rooms	0.51	0.5	0.26	0.1	0.51
Total	1.13		12.63		0.230
Time weighted average		11.14		0.20	

Figure 4.1, continued

b) Activity log

ACTIVITY LOG

Requesting Department	Examination	Room	Film	Time of Request	Travel Mode	Arrival Time	Completion Time	Remarks	For Department Use Only		
									De [initials]	A [initials]	V [initials]
58 U-30	C Spine	1020		9	A	700	730	Moore	✓	✓	
0 U-30	left knee	1070		2	A	730	810	Wichler	✓	✓	
69 Brain	Brain	1070				810	840	Welch	✓	✓	
1077 Vag	Spine	1075				920	1015	Maguire	✓	✓	✓
34 U-30	Brain	1010				1020	1100		✓	✓	
33 U-30	Brain	1070				1130	1150	Schumann	✓	✓	
U-30	Brain - Hysty	1070	U10			1155	1230	Yapp, C	✓	✓	
36 Vag	Brain	1070				1230		Kumar	✓	✓	✓
	Brain cont.	1070					1305		✓	✓	✓
4 OC	Brain	1070				1320	1340	Wick	✓	✓	✓
19 OC	Brain	1070				1410	1435	Sack	✓	✓	
7 M	Brain	1070		2000		1450		Coker	✓	✓	
	Brain, lum 2	1073					1545	+	✓	✓	
19 VA	Brain	1075		1500		1615		Vah	✓	✓	✓
	Brain, lum 2	1075					1645		✓	✓	✓
8 VA	C Spine	1075		used		1620		Vah	✓	✓	
U	L Spine	1075				1700		Burke	✓	✓	
	L Spine, lum 2	1075					1810		✓	✓	
08 U-30	Brain	1075				1810	1840	Moore	✓	✓	
15 U	Brain	1075				1815		Burdick	✓	✓	
	Brain, lum 2	1075					1920	+	✓	✓	
7 VA	Brain	1075				1930		Vah	✓	✓	✓
	Brain, lum 2	1075					2005	+	✓	✓	✓
3 U	L Spine	1075				2015	2055	William	✓	✓	
78 VA	TACS										

5.0 Safety Procedures

The presence of a large static magnetic field introduces unique safety concerns for personnel and the equipment. Protocols for exposure measurements must describe safety-related actions. Measurement personnel must be thoroughly versed in the hazards associated with strong fields and aware of the precautionary measures to avoid problems. Safety in an MRI facility is clearly a responsibility and concern of the facility operators. Measurement personnel will therefore follow all safety and operating procedures at a facility and have all their specific measurement procedures approved by facility staff before proceeding. Measurement personnel not familiar with MRI facilities will be required to view a videotape on MRI facility safety.

The primary safety concern for measurement personnel is the effect the high static field can have on ferromagnetic objects: the field can produce large torques on fixed objects and the nonuniformity of the field can cause a strong force to be exerted on objects. Both of these effects can result in uncontrollable and dangerous movement of objects in the MRI exam room. These "missiles" can cause injury or, if lodged in the magnet, can degrade quality of the MRI image. Normally all ferromagnetic objects are excluded from the MRI exam room. This is done by screening personnel, removing personal objects from clothes and by ensuring that objects taken into the room are non-magnetic.

5.1 Personnel Screening

Because metal implants in the body are potentially hazardous and because performance of measurements will require time in fields comparable to those which patients experience, each person who will perform the measurement procedures will fill out a checklist similar to that for interviewing patients. A sample checklist is shown in Figure 5.1 [Edelman and Hesselink, 1990, p. 68]. A simpler checklist employed by the OHSU MRI facility (Figure 5.2) was filled out by investigators prior to the measurements on February 28, 1993. With such a checklist filled out and available, the facility operators can quickly assess the advisability of a person entering the MRI exam room. MRI facility personnel who are assisting with the measurements need not fill out the questionnaire.

Wearers of surgical implants such as pacemakers, aneurysm clips, artificial cochleas, biostimulators, artificial heart valves and orthopedic prostheses will be excluded from performing measurements and may even be excluded from areas in the facility with fields greater than 0.05T (Edelman and Hesselink, 1990, p. 354).

5.2 Personal Effects

All personal effects that could become missiles or be damaged will be removed from the person and left outside the MRI exam room. These include: keys, watch, credit cards, beeper, hairpins, paper clips and pens. The need for constant vigilance until personnel become familiar with routine procedures in an MRI facility was demonstrated during the measurements reported here: after lunch the principal investigator carried his wallet into the MRI room, resulting in the demagnetization of all credit cards.

5.3 Measurement Equipment

The measurement probes that were used in the MRI room were constructed of non-ferromagnetic material to the extent possible. The probes used in the procedure evaluation were assessed for magnetization as they were moved into the MRI exam room. Peripheral equipment such as probe stands, clipboards, etc. was constructed of non-magnetic materials and also checked as it was brought into the MRI facility. Only measurement probes were taken into the MRI exam room.

Figure 5.1 Sample checklist for MRI measurement personnel (Edelman and Hesselink, 1990, p. 68).

Appendix 2-A

SAMPLE CHECKLIST AND WORK-UP SHEET FOR INTERVIEWING PATIENTS*

2.—Practical MRI for the Technologist and Imaging Specialist—Appendix A / 69

Have you ever worked in a machine shop or similar environment where you may have been subjected to small metal shavings? yes no
 Have you ever had an injury to your eye involving metal? yes no
 Are you pregnant or do you suspect that you are pregnant? yes no
 How many months? _____

Last menstrual period: _____
 Post menopausal? yes no
 If you are having an MRI procedure involving the abdominal area, list what you've eaten last 4 hours: _____

DATE _____
 NAME _____
 SEX _____ AGE _____ PHYSICIAN # _____ PATIENT # _____
 DATE OF BIRTH _____ HEIGHT _____ WEIGHT _____ IN PATIENT _____
 PROCEDURE _____ OUT PATIENT _____

DIAGNOSIS _____
 CLINICAL HISTORY _____

THE FOLLOWING ITEMS MAY INTERFERE WITH MAGNETIC RESONANCE IMAGING AND SOME CAN BE POTENTIALLY HAZARDOUS. PLEASE INDICATE IF YOU HAVE THE FOLLOWING:

- cardiac pacemaker yes no
- aneurysm clips yes no
- implanted insulin pump yes no
- implanted drug infusion device yes no
- laser growth stimulator yes no
- neuromodulator (TENS, UHS) yes no
- any type of bio-stimulator yes no
- internal hearing aid yes no
- cardiac implant yes no
- Chamberlain coil (tipping catheter coil) yes no
- vascular clips yes no
- hemostatic clips yes no
- any type of surgical clip or staple(s) yes no
- heart valve prosthesis yes no
- Greenfield venous sinus filter yes no
- middle ear implant yes no
- penile prosthesis yes no
- orthopedic prostheses yes no
- atrial septal or buffer yes no
- wire sutures yes no
- tattooed eyeliner yes no
- any type of dental item held in place by a magnet yes no
- any other implanted item yes no
- type: _____

- diaphragm yes no
- IUD yes no
- renal shunt yes no
- intraventricular shunt yes no
- wire mesh yes no
- artificial limb or joint yes no
- any orthopedic item(s) (i.e., pins, rods, screws, nails, clips, plates, wires, etc.) yes no
- dentures yes no
- dental braces yes no
- any type of removable dental item yes no

Have you ever had a surgical procedure or operation of any kind? yes no
 Type: _____

PERTINENT PREVIOUS STUDIES: Diagnostic X-rays _____
 Computed tomography _____
 Ultrasound _____
 Radionuclide study _____

I attest that the above information is correct to the best of my knowledge.

(Patient's Signature)

MD/DR/RT Signature _____ Date _____

Print MD/DR/RT Name _____

Please mark on this drawing the location of any metal inside your body.

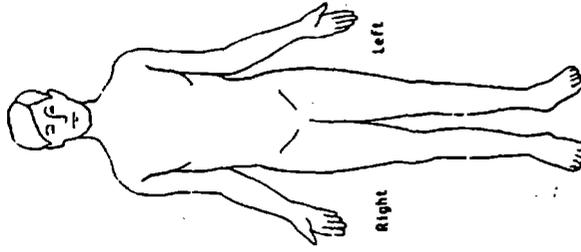


Figure 5.2 OHSU MRI facility patient checklist.

DATE: _____ HEIGHT _____ WEIGHT _____
NAME: _____ DATE OF BIRTH: _____
MEDICAL RECORD NUMBER (OHSU pts.) _____
SOCIAL SECURITY NUMBER (VA pts.) _____
Have you ever had an MRI: NO ___ YES ___ IF YES, WHERE _____

DUE TO THE HIGH STRENGTH OF THE MAGNETIC FIELD, THE FOLLOWING MAY AFFECT THE PICTURES AND/OR BE HAZARDOUS TO YOUR SAFETY:

PLEASE MARK ANY ITEMS THAT APPLY TO YOU:

- CARDIAC PACEMAKER
- HEART VALVE; DATE _____ TYPE/MANUFACTURE _____
- HAVE YOU EVER HAD ANY TYPE OF METAL IN YOUR EYES
- METALLIC FOREIGN OBJECTS ie; Schrapnel, Metal, Implants
- ANEURYSM CLIPS; Aortic vs Cerebral; Date of Surgery _____
- SURGICAL CLIPS; TYPE _____
- HEARING AIDS
- COCHLEAR IMPLANTS
- TENS UNIT IMPLANTED IN THE BODY
- PREGNANT/NURSING ___
- ANY TYPE OF IMPLANT
- DENTURES

PLEASE DESCRIBE YOUR SYMPTOMS:

A LOCKER IS PROVIDED TO SECURE YOUR VALUABLES. YOU MAY TAKE THE LOCKER KEY INTO THE SCAN ROOM WITH YOU. WE ARE NOT RESPONSIBLE FOR ANY ITEMS LOST OR LEFT IN THE DEPARTMENT.

This document is to remain in the patients permanent radiology file folder.

6.0 Solicitation Procedures for Future Study

The procedure for soliciting facilities in an exposure assessment protocol will entail mailing a solicitation packet to all eligible facilities. This packet will include: a cover letter explaining the purpose of the project and requesting their participation; a project description that details measurement, time-motion and time allocation procedures; an assessment of participation requirements and impacts; a facility information sheet; and a participation agreement form that includes the necessary disclaimers. These documents can only be finalized after the study is designed and protocols developed. For the sake of example, a sample cover letter and site information form are presented below. Other documents such as the project description, assessment of impacts on the facility and participation agreement can only be prepared after the exposure assessment study has been designed.

6.1 Cover Letter

A sample cover letter that could be sent to MRI facility directors for the purpose of soliciting participation in an exposure assessment study is given in Figure 6.1.

6.2 Site Information Form

A draft site information form for acquiring initial information about a facility is shown in Figure 6.2. The actual form would be developed after the study design is completed and sampling strata identified.

Figure 6.1: Draft of cover letter to solicit participation in MRI exposure assessment project.

NIOSH
4676 Columbia Parkway
Cincinnati, OH

Dr. M.R. Image, Director
MRI Facility XYZ
Anytown, USA

Re: MRI Exposure Assessment Project

Dear Dr. Image:

The National Institute for Occupational Safety (NIOSH) and the National Cancer Institute (NCI) are collaborating on a project to assess exposures of magnetic resonance imaging (MRI) workers to electric and magnetic fields associated with the use of this technology. The exposure information gained in this project will be used in an epidemiologic study of MRI workers. The purpose of this letter is to describe the project and solicit the participation of your facility in this effort.

Over 2250 MRI facilities across the country are being asked to participate in this effort. After sufficient responses have been received, approximately 50 sites will be selected at random for participation. Should you agree to participate, your facility may not be selected to be measured, but your response to the attached facility information form will be included in the analysis of site characteristics and activities. The results of the study will be published and all respondents to this letter will receive a copy of the final report. The entire project is expected to require one year.

The MRI exposure assessment procedure entails three components: characterization of the fields; estimates of time spent by personnel in certain work areas during specific procedures; and estimates of the number and time spent for various procedures over the course of a month. Procedures and protocols have been developed to address each of these facets of the exposure assessment process. The procedures are described in detail in the accompanying Project Description.

[Insert brief description of final field measurement protocol.] A project team member will perform the measurements at your facility with assistance from a member of your staff. The measurements should be made during non-clinical hours and will require approximately one hour. Each participating site will receive a summary of measurements made at their facility. Measurement personnel have been instructed in safety procedures and all instrumentation and probes have been designed for safe use in the MRI facility environment. Approval for all procedures will be obtained from appropriate person(s) at your facility prior to implementation.

To determine time spent during various MRI procedures over the course of a day will require that two technologists maintain time/location logs over the course of two days each. These logs will be kept on standard forms. Instruction on the time keeping protocols will be provided by the project team member who performs the measurements. The time logs will be mailed directly to project headquarters. Participants names will be optional on the form to ensure anonymity. This information will allow time spent in work areas with known field characteristics to be quantified for various procedures.

Allocations of time for different MRI procedures will be estimated from the log of operations at your site. While the project team member is at your site, he/she will compile data on procedures -- type, number and duration -- that were performed at your site during two months of the past year. This information will

Figure 6.1 continued

be extracted from MRI system logs or other records onto standardized forms. This information will allow estimates of the overall time spent during a year performing various procedures.

Interest in electric and magnetic fields as an environmental agent has emerged only relatively recently, primarily because several epidemiological studies have raised the question of whether exposures to power frequency magnetic fields in occupational and residential environments are associated with cancer. It is important to emphasize that the suggested association between cancer and indirectly determined field exposures is not strong, and magnetic fields cannot be identified as a causal agent. Numerous scientific panels have reviewed the research literature on biological effects related to low frequency electric and magnetic fields. These groups generally conclude that the studies do not show any health effects to the general public or electric utility workers from short term or long term exposure to fields found around utility generation and distribution equipment.

The purpose of the present study is to extend our knowledge of magnetic field exposures and possible effects to the unique magnetic fields of the MRI facility environment. This exposure assessment project is an important aspect of the epidemiologic study because of the need to measure exposures rather than rely on surrogates.

We look forward to a favorable response to this request and will appreciate your willingness to participate. If you are willing to participate, please complete and sign the participation agreement and return it, along with the facility information form, in the enclosed envelope.

If you have questions regarding the project or your participation, please call the Project Manager, Dr. E. X. Posure at (513) 555-9999.

Sincerely,

Joe Bowman, Ph.D.

Figure 6.2 Draft Site Information Form for MRI Exposure Assessment Study

Site Information Form

Facility:	
Address:	
Telephone:	Fax:
Director:	Telephone:
Facility operations manager:	Telephone:
Contact for scheduling:	Telephone:
Location: Hospital ___; Medical Clinic ___; MRI Clinic ___; Mobile ___	
MRI System: Vendor: _____ Model: _____	
Magnet: Field in bore: _____ T Type: superconducting, resistive, permanent	
RF Frequency(ies): _____MHz _____MHz	
Facility utilization: Clinic Hours/day _____ Clinic Days/week _____ Non-clinic hours/week _____	
Personnel: Full time: technologists _____; other routinely in exam room _____ Other staff _____	
Site plan: Please sketch or provide a site layout of the MRI facility showing the exam room, control room, computer room and other areas. Please include approximate dimensions of the exam and control rooms.	
Comments:	

7.0 Recommendations for Exposure Assessment Procedures

The objective of this study was to develop and evaluate electric and magnetic field exposure assessment methodologies for MRI facility workers. Although hampered by instrument problems, the results of the field measurements and procedure evaluation at the OHSU MRI facility provide a characterization of fields present in that facility and indicate fruitful directions for additional research as embodied in the following recommendations.

7.1 General Approach

This initial effort was limited in scope and resources, especially in areas related to access and operation of an MRI facility. Therefore, further efforts should:

- Include sufficient resources, including time in an MRI facility, to examine each exposure parameter separately;
- Test instruments in MRI environment, or equivalent, prior to scheduled facility use;
- Include a research team member familiar with MRI system operation on a day-to-day basis; and
- Have ready access to an MRI facility and cooperation of its staff while developing exposure assessment methodology.

7.2 Static Field Characterization

Based on static field measurements made during this project, the following are recommended:

- Utilize static field contours (including any shielding) provided by system manufacturers to assign fields to work areas; and
- Test the Seiko dosimeter against modeled exposures over the period of a day for normal MRI facility operations. (See below for recommended modifications to dosimeter.)

7.3 Gradient Field Characterization

Recommendations related to gradient field characterization are:

- Identify a standard simple pulse sequence that produces maximum resultant field at the magnet bore; utilize the standard pulse sequence at each facility for characterization of gradient fields near the magnet; and
- Utilize a wave capture system, such as the Multiwave™ with the existing measurement staff to more thoroughly investigate gradient field dependence on scanning protocols and sequence parameters, including measurements with the MRI system off.

7.4 Radio Frequency Field Characterization

The failure to adequately measure RF fields during this study should be rectified by the following:

- Utilize appropriate instrumentation to characterize RF levels in MRI room and confirm low levels outside of magnet. Preferred instrumentation would have narrow band response with capability to record RF pulse sequences; and
- If low RF levels are confirmed, do not include RF measurements in facility characterization

7.5 Instrumentation

The following recommendations apply to instrumentation:

- Explore modification of the Seiko dosimeter to include three ranges for recording time and integrated exposure: $B < 10 \text{ mT}$; $10 \text{ mT} < B < 100 \text{ mT}$; and $B > 100 \text{ mT}$; and
- Modify Multiwave™ system to eliminate RF interference with gradient field preamplifiers; to allow external triggering of waveform capture; and to accurately respond to pulsed fields (change frequency response of input).

7.6 Time/Location Monitoring

At present, one of the principal unknowns for exposure assessment is the amount of time spent in the work area with the highest fields. The following recommendations are directed towards obtaining that information and enhancing the process of estimating the time/location component of exposure assessment.

- Observe technicians with TimeWand® at several different facilities during normal operations to obtain estimates of variability in time spent in work areas as a function of protocols and site-specific procedures;

- Develop and test self-reporting time/location log for technicians to estimate time spent within specified distance of magnet; and
- Compile frequency and duration data from activity logs at several facilities to estimate variability between sites and identify most frequently performed protocols.

7.7 Exposure Assessment

The following recommendations relate to the information requirements and integration of various components that are involved with exposure assessment:

- Locate and, if available, obtain database on characteristics of existing MRI facilities;
- Develop facility survey form to obtain information germane to exposure assessment;
- Identify MRI systems in use and obtain static field contour data from manufacturers. Also request additional field measurement data from manufacturers including RF field measurements;
- Assess the variability between sites of field levels, of time spent near magnet, and of the frequency of performance of MRI scans in order to identify the principal sources of variability in the exposure assessment process; and
- Investigate the possibility that facility activity records can be obtained from the MRI computer, using software from the MRI manufacturer.

8.0 References

Edelman, Robert R and Hesselink, John R (eds.), Clinical Magnetic Resonance Imaging, 1990, W. B. Saunders Company, Philadelphia.

9.0 Acknowledgements

During the development and testing of the measurements and procedures described here, personnel from the OHSU MRI facility were very informative and cooperative. Patrice Manley and Dr. Jerzy Szumowski were very helpful in providing background information on the operation and procedures of the facility and in scheduling time for measurements. Dr. Szumowski was also present during the evaluation, where he shared his expertise on MRI fields and provided guidance in the implementation of testing protocols. Kathy Griffith was the MRI operator during the evaluation. William Jacobs of Electric Research and Management, Inc. (ERM) very ably and patiently operated the Multiwave™ System in the presence of instrumental uncertainties during the evaluation process. His colleagues at ERM, Inc., Fred Dietrick and William Gish provided valuable technical support during the measurements and analyses. Russell Senior of T. Dan Bracken, Inc. developed the support software and procedures for barcode scanning of time/location information and also performed the scanning during the evaluation of the procedure. The participation and support of the NIOSH project manager, Dr. Joseph Bowman, is also gratefully acknowledged: his participation in the evaluation and his comments throughout the project have made a valuable contribution.

Appendix A: Multiwave™ Datafiles

Data file	Measurement Location	Description
a) Static field		
HAA 001	05	Sensor 1.1 m height; in stand
HAA 002	05	Sensor 1.1 m; handheld
b) Gradient field		
COA 001	03	Vertical staff; maximum gradient field
COA 002	03	Vertical staff; one-half maximum gradient field
COA 003	03	Vertical staff; one-quarter maximum gradient field
COB 001	03	Vertical staff; in stand
COB 002	03	Vertical staff; handheld
COC 001	01	Horizontal staff on patient table
COC 002	02	Vertical staff; at magnet
COC 003	03	Vertical staff; at magnet
COC 005	05	Vertical staff; at magnet
COC 006	06	Vertical staff; at magnet
COC 007	07	Vertical staff; at patient table
COC 008	08	Vertical staff; at patient table
COC 009	09	Vertical staff; at patient table
COC 010	10	Vertical staff; at patient table
COC 011	11	Vertical staff; at patient table
COC 012	12	Vertical staff; in MRI room
COC 013	13	Vertical staff; in MRI room
COC 014	14	Vertical staff; in MRI room
COC 015	15	Vertical staff; in control room
COC 016	16	Vertical staff; at rf cabinet in control room
COC 017	17	Vertical staff; at console in control room
COC 018	18	Vertical staff; at console in control room
COC 019	19	Vertical staff; in control room

Data file	Measurement Location	Description
COC 020	20	Vertical staff; in control room
COC 021	21	Vertical staff; in hallway
COC 022	22	Vertical staff; in hallway
COC 023	23	Vertical staff; in hallway
COC 024	24	Vertical staff; in computer room at tape drives
COC 025	25	Vertical staff; in computer room at rf power supply
COC 026	26	Vertical staff; in computer room at gradient power supply
COC 115	15	Vertical staff; gradient field off
COC 120	20	Vertical staff; gradient field off
COC 122	22	Vertical staff; gradient field off
COC 124	24	Vertical staff; gradient field off
COC 125	25	Vertical staff; gradient field off
COC 126	26	Vertical staff; gradient field off
COD 001	01	Horizontal staff; FOV=8 cm; t=3 mm
COD 002	01	Horizontal staff; FOV=48 cm; t=3 mm
COD 003	01	Horizontal staff; FOV=48 cm; t=2 cm
c) RF field		
REA 001	90 cm in bore	Spin echo; TE=10 ms; TR=40 ms
REB 001	0 cm in bore	Spin echo; TE=10 ms; TR=40 ms
REC 001	90 cm in bore	Spin echo; TE=11 ms; TR=600 ms
RHA 001	90 cm in bore	Spin echo; TE=10 ms; TR=40 ms
RHB 001	0 cm in bore	Spin echo; TE=10 ms; TR=40 ms
RHC 001	90 cm in bore	Spin echo; 0dB; TE=11 ms; TR=600 ms
RHC 002	90 cm in bore	Spin echo; -20dB; TE=11 ms; TR=600 ms
RHC 003	90 cm in bore	Spoiled gradient; 0dB;
RHC 004	90 cm in bore	Fast spin echo; 0dB;

Multiwave Datafile Summary: Hall Effect Probe

HAA001

Site: Hall Effect Probe Setup

Prefix: HAA

Dataset: 001

> Hall Effect Probe

>

>

Start: 02/28/93 (Sunday) AT 09:55:55

End: 02/28/93 (Sunday) AT 09:56:10

Recorded 3 samples at 5 seconds intervals

AMP UNIT PROBES DEPLOYED = 4

1 [P1]

CHAN A:

CHAN B:

CHAN C: Hall Effect Probe - X-Axis Temperature

2 [P2]

CHAN A:

CHAN B:

CHAN C: Hall Effect Probe - Y-Axis Temperature

3 [P3]

CHAN A:

CHAN B:

CHAN C: Hall Effect Probe - Z-Axis Temperature

15 [P5] Hall Effect Probe (AC)

CHAN A: Hall Effect Probe (AC) - X-Axis

CHAN B: Hall Effect Probe (AC) - Y-Axis

CHAN C: Hall Effect Probe (AC) - Z-Axis

DIRECT PROBES DEPLOYED = 1

5 [P5] Hall Effect Probe (DC)

CHAN A: Hall Effect Probe (DC) - X-Axis

CHAN B: Hall Effect Probe (DC) - Y-Axis

CHAN C: Hall Effect Probe (DC) - Z-Axis

SAMPLE PARAMETERS

DACBOARD 1

Clock source: INTERNAL

Trigger source: GATED

Sample points per waveform: 128

Mux Input	Base Freq	Sample Freq	Actual
ALL	1.00	128.00	128.01

DACBOARD 2

Clock source: INTERNAL

Trigger source: GATED

Sample points per waveform: 2048

Mux Input	Base Freq	Sample Freq	Actual
ALL	5.00	10240.00	9259.26 10256.4

AUTORANGING SETUP

Global autoranging: OFF

Float-to-max range: OFF

Multiwave Datafile Summary: Hall Effect Probe, continued

HAA001

PROBE	RANGE SETTINGS	AUTO-RANGING
# 1 [P1]	CHAN A: 5.00 V	ON
	CHAN B: 5.00 V	ON
	CHAN C: 5.00 V	ON
# 2 [P2]	CHAN A: 5.00 V	ON
	CHAN B: 5.00 V	ON
	CHAN C: 5.00 V	ON
# 3 [P3]	CHAN A: 5.00 V	ON
	CHAN B: 5.00 V	ON
	CHAN C: 5.00 V	ON
# 15 [P5]	Hall Effect Probe (AC)	
	CHAN A: 10000 G	ON
	CHAN B: 9980 G	ON
	CHAN C: 9770 G	ON
# 5 [P5]	Hall Effect Probe (DC)	
	CHAN A: 5000 G	OFF
	CHAN B: 4990 G	OFF
	CHAN C: 4885 G	OFF

Multiwave Datafile Summary: Gradient Field Probe

COC001

Site: ~~Hall Effect~~ ^{Gradient Field} Probe Setup

Prefix: COC

Dataset: 001

> ELF, VLF, and LF with Coils

>

>

Start: 02/28/93 (Sunday) AT 11:37:45

End: 02/28/93 (Sunday) AT 11:38:00

Recorded 3 samples at 5 seconds intervals

AMP UNIT PROBES DEPLOYED = 8

1 [P1]

CHAN A: Staff Position 1 (LF) 170cm - RMS
 CHAN B: Staff Position 1 (VLF) 170cm - RMS
 CHAN C:

2 [P2]

CHAN A: Staff Position 2 (LF) 110cm - RMS
 CHAN B: Staff Position 2 (VLF) 110cm - RMS
 CHAN C:

3 [P3]

CHAN A: Staff Position 3 (LF) 110cm - RMS
 CHAN B: Staff Position 3 (VLF) 110cm - RMS
 CHAN C:

4 [P4]

CHAN A: Staff Position 4 (LF) 80cm - RMS
 CHAN B: Staff Position 4 (VLF) 80cm - RMS
 CHAN C:

11 [P1]

Staff Position 1 (ELF) 170cm
 CHAN A: Staff Position 1 (ELF) 170cm - X-Axis
 CHAN B: Staff Position 1 (ELF) 170cm - Y-Axis
 CHAN C: Staff Position 1 (ELF) 170cm - Z-Axis

12 [P2]

Staff Position 2 (ELF) 140cm
 CHAN A: Staff Position 2 (ELF) 140cm - X-Axis
 CHAN B: Staff Position 2 (ELF) 140cm - Y-Axis
 CHAN C: Staff Position 2 (ELF) 140cm - Z-Axis

13 [P3]

Staff Position 3 (ELF) 110cm
 CHAN A: Staff Position 3 (ELF) 110cm - X-Axis
 CHAN B: Staff Position 3 (ELF) 110cm - Y-Axis
 CHAN C: Staff Position 3 (ELF) 110cm - Z-Axis

14 [P4]

Staff Position 4 (ELF) 80cm
 CHAN A: Staff Position 4 (ELF) 80cm - X-Axis
 CHAN B: Staff Position 4 (ELF) 80cm - Y-Axis
 CHAN C: Staff Position 4 (ELF) 80cm - Z-Axis

SAMPLE PARAMETERS

DACBOARD 1

Clock source: INTERNAL

Trigger source: GATED

Sample points per waveform: 128

Mux Input	Base Freq	Sample Freq	Actual
ALL	1.00	128.00	128.01

DACBOARD 2

Clock source: INTERNAL

Trigger source: GATED

Sample points per waveform: 2048

Mux Input	Base Freq	Sample Freq	Actual
ALL	5.00	10240.00	10156.4 9259.26

AUTORANGING SETUP

Global autoranging: OFF

Float-to-max range: OFF

Multiwave Datafile Summary: Gradient Field Probe, continued

COC001

PROBE	RANGE SETTINGS	AUTO-RANGING
# 1 [P1]	CHAN A: 29.6mG CHAN B: 168mG CHAN C: 5.00	ON ON ON
# 2 [P2]	CHAN A: 8.64mG CHAN B: 48.9mG CHAN C: 5.00	ON ON ON
# 3 [P3]	CHAN A: 2.83mG CHAN B: 16.1mG CHAN C: 5.00	ON ON ON
# 4 [P4]	CHAN A: 0.85mG CHAN B: 4.81mG CHAN C: 5.00	ON ON ON
# 11 [P1]	Staff Position 1 (ELF) 170cm CHAN A: 2540mG CHAN B: 2560mG CHAN C: 2310mG	ON ON ON
# 12 [P2]	Staff Position 2 (ELF) 140cm CHAN A: 753mG CHAN B: 726mG CHAN C: 684mG	ON ON ON
# 13 [P3]	Staff Position 3 (ELF) 110cm CHAN A: 231mG CHAN B: 240mG CHAN C: 238mG	ON ON ON
# 14 [P4]	Staff Position 4 (ELF) 80cm CHAN A: 71.4mG CHAN B: 70.8mG CHAN C: 70.8mG	ON ON ON

Multiwave Datafile Summary: RF Field Probe

REB001

RF Field
Site: ~~Ball-Effect~~ Probe Setup
Prefix: REB
Dataset: 001
> R.F. Probe
>
>

Start: 02/28/93 (Sunday) AT 09:26:25
End: 02/28/93 (Sunday) AT 09:26:40
Recorded 3 samples at 5 seconds intervals

AMP UNIT PROBES DEPLOYED = 1
4 [P4]
CHAN A:
CHAN B:
CHAN C: R.F. Probe

SAMPLE PARAMETERS

DACBOARD 1
Clock source: INTERNAL
Trigger source: GATED
Sample points per waveform: 128
Mux Input Base Freq Sample Freq Actual
ALL 1.00 128.00 128.01
DACBOARD 2
Clock source: INTERNAL
Trigger source: GATED
Sample points per waveform: 2048
Mux Input Base Freq Sample Freq Actual
ALL 5.00 10240.00 ~~9259.26~~
10256.4

AUTORANGING SETUP

Global autoranging: OFF
Float-to-max range: OFF

REB001

PROBE	RANGE SETTINGS	AUTO-RANGING
# 4 [P4]		
CHAN A:	5.00	ON
CHAN B:	5.00	ON
CHAN C:	12.0 V	ON

Appendix B:

Documentation of TimeWand® Support Programs for the MRI Project
February 12, 1993
Russell S. Senior

TimeWand® SUPPORT PROGRAMS

Two programs have been written to support the collection and analysis of data from the NIOSH/MRI project using the VIDEX TimeWand® bar code scanning system: the MRIWAND program is used to download information from the TimeWand® bar code reader; the MRITIME program is used to generate a report from recorded data of where time was spent by subjects.

The MRIWAND program requires a single command-line argument, *<filename>*, the name of the file to which information will be downloaded. The program is executed by typing:

MRIWAND *<filename>*

when in the TimeWand® program directory. The MRIWAND program sets up and executes a command to download the data from a TimeWand® using the Videx DLOAD program. The command it executes is:

DLOAD -iWAND.TXT -o*<filename>* -t70 -c2 -sSTATUS.TXT > DLOAD.OUT

where *<filename>* is the full filename specified by the MRIWAND command-line argument. The file **WAND.TXT** must be present and correct for the command to succeed. (See the VIDEX TimeWand® System Manual for information on operating the TimeWand® hardware and software.)

After the data file has been downloaded with MRIWAND, the MRITIME program can be executed on the downloaded file to generate a report of the duration that the wanded subjects spent in the defined locations. The MRIWAND program calls this reporting program with the following command:

MRITIME *<filename>*

where *<filename>* is the name of the file containing downloaded data as described above.

USE OF TIMEWAND BAR CODE READERS:

The MRITIME program has been written with several assumptions about how the barcode readers will be used. If these assumptions are violated the program may generate inaccurate information or may fail to operate at all.

The barcode reader will be used to record the locations of up to three MRI personnel during specific MRI-related procedures. One or more procedures may be recorded before downloading the information from the barcode reader. At the start of each procedure, the barcode reader will scan in the appropriate procedure start code. Thereafter, locations of the personnel will be scanned as their locations change. Each time a person enters a different area, the code for that area and person is scanned. Any time that elapses between the start of the procedure and the first scan for a person is ignored. At the conclusion of each procedure, the procedure end code labeled "END" on the scan card is scanned. A new procedure should not be started until an end for the previous one has been recorded. A failure to properly end a procedure will result in incomplete or erroneous results. The system has a limited mechanism for correcting errors using the barcode reader itself. If a scan is made in error, then a barcode identified as "ERROR" on the scan card may be used to modify the last non-error code scanned. The first code scanned after the error code will be considered to have been scanned at the time of the code prior to the error code. Sequential error codes are considered as a single error code.

When a number of procedures have been recorded, the barcode reader may be downloaded. Insert the barcode reader into the TimeWand® charger/communication device. Initiate the downloading software with an appropriate filename. If the filename already exists, the information will be appended to it. For example, you might type the following command:

MRIWAND TEST.BCD

Observe the LEDs in the charger unit. When the RECEIVE light begins to blink, you may press the barcode reader button to initiate the download. If you fail to press the button, the barcode reader should begin downloading by itself within a minute or so.

When the download is complete, the MRITIME program is run and the results are listed to the screen. If more than one screen full of information is generated then you may not have a chance to review the results fully. If this occurs, type the MRITIME command and use the standard DOS program MORE to see the output a page at a time:

MRITIME TEST.BCD | MORE

The MRIWAND and MRITIME program could bear considerable improvement. A facility for automatically naming the files according to some convention, another for maintaining a history of the downloaded information and status files, and a better system for viewing the output of the MRITIME program are possibilities for the future.

Consult the TimeWand® system manual for information on operating the TimeWand® scanner and software.

When a number of procedures have been recorded, the barcode reader may be downloaded. Insert the barcode reader into the TimeWand® charger/communication device. Initiate the downloading software with an appropriate filename. If the filename already exists, the information will be appended to it. For example, you might type the following command:

MRIWAND TEST.BCD

Observe the LEDs in the charger unit. When the RECEIVE light begins to blink, you may press the barcode reader button to initiate the download. If you fail to press the button, the barcode reader should begin downloading by itself within a minute or so.

When the download is complete, the MRITIME program is run and the results are listed to the screen. If more than one screen full of information is generated then you may not have a chance to review the results fully. If this occurs, type the MRITIME command and use the standard DOS program MORE to see the output a page at a time:

MRITIME TEST.BCD | MORE

The MRIWAND and MRITIME program could bear considerable improvement. A facility for automatically naming the files according to some convention, another for maintaining a history of the downloaded information and status files, and a better system for viewing the output of the MRITIME program are possibilities for the future.

Consult the TimeWand® system manual for information on operating the TimeWand® scanner and software.

Summary derived from information collected with a TimeWand barcode reader at Oregon Health Sciences University, 28 February 1993:

MRI Time Wand Analysis

Data downloaded to oshutest.bcd from wand#1000 at Sun Feb 28 16:03:20 1993
(289 lines read)

Protocol 1

Started at: Sun Feb 28 14:54:04 1993
Finished at: Sun Feb 28 16:02:20 1993
Elapsed: 1:08:16

Location	<i>Joe</i> Person 1	<i>Don</i> Person 2	<i>Yurik</i> Person 3
Control Room	16:00 (23.4%)	31:44 (46.7%)	6:24 (9.4%)
@Console	10:56 (16.0%)	0:00 (0.0%)	33:20 (49.0%)
MRI Room	5:36 (8.2%)	3:28 (5.1%)	1:52 (2.7%)
@Patient	1:20 (2.0%)	2:08 (3.1%)	1:20 (2.0%)
@Magnet	3:44 (5.5%)	3:28 (5.1%)	1:36 (2.4%)
Computer Room	0:00 (0.0%)	0:32 (0.8%)	0:32 (0.8%)
Other Rooms	30:40 (44.9%)	26:40 (39.2%)	22:56 (33.7%)
Total	1:08:16 (100.0%)	1:08:00 (100.0%)	1:08:00 (100.0%)

Report derived from a TimeWand file, OHSUTEST.BCD:

H 19930228160320 00 0000001000
 19930228145404 00 P01
 19930228145404 00 015
 19930228145420 00 027
 19930228145420 00 037
 19930228145420 00 021
 19930228145436 00 031
 19930228145436 00 013
 19930228145452 00 032
 19930228145508 00 031
 19930228145508 00 037
 19930228145508 00 011
 19930228145524 00 017
 19930228145540 00 031
 19930228145540 00 032
 19930228145556 00 011
 19930228145556 00 012
 19930228145612 00 011
 19930228145628 00 012
 19930228145700 00 011
 19930228145700 00 013
 19930228145732 00 011
 19930228145748 00 017
 19930228145852 00 011
 19930228145908 00 012
 19930228145924 00 011
 19930228145940 00 013
 19930228145956 00 011

19930228150236 00 012
19930228150308 00 011
19930228150308 00 013
19930228150324 00 011
19930228150324 00 OER
19930228150324 00 033
19930228150340 00 031
19930228150340 00 032
19930228150340 00 012
19930228150356 00 011
19930228150412 00 017
19930228150604 00 011
19930228150604 00 012
19930228150636 00 011
19930228150724 00 013
19930228150740 00 011
19930228150844 00 023
19930228150844 00 025
19930228150844 00 013
19930228150844 00 025
19930228150900 00 OER
19930228150900 00 015
19930228150900 00 014
19930228150900 00 013
19930228150916 00 024
19930228150916 00 014
19930228150932 00 013
19930228150932 00 023
19930228150932 00 011
19930228150932 00 021
19930228150948 00 017
19930228150948 00 011
19930228150948 00 013
19930228151020 00 013
19930228151108 00 011
19930228151124 00 013
19930228151140 00 011
19930228151156 00 017
19930228151212 00 011
19930228151228 00 017
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19930228151332 00 011
19930228151420 00 023
19930228151420 00 017
19930228151436 00 011
19930228151436 00 021
19930228151612 00 023
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19930228151612 00 025
19930228151612 00 014
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19930228151628 00 014
19930228151628 00 013
19930228151628 00 011
19930228151628 00 024
19930228151644 00 023
19930228151700 00 017

19930228151716 00 021
19930228151732 00 011
19930228151732 00 023
19930228151732 00 025
19930228151732 00 013
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19930228151748 00 031
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19930228151836 00 031
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19930228151836 00 033
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19930228151908 00 023
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19930228151940 00 023
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19930228151956 00 035
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19930228151956 00 017
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19930228152012 00 027
19930228152012 00 033
19930228152012 00 031
19930228152028 00 011
19930228152028 00 036
19930228152028 00 013
19930228152028 00 014
19930228152044 00 031
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19930228152044 00 011
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19930228152132 00 037
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19930228152148 00 032

19930228152148 00 031
19930228152204 00 033
19930228152204 00 021
19930228152204 00 034
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19930228152220 00 015
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19930228152252 00 021
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19930228152308 00 024
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19930228152324 00 015
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19930228152428 00 013
19930228152428 00 033
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