Assessment of Learning Using a Remote Access Magnetic Resonance Imaging Laboratory: Initial Experience

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Abstract

The extremely high cost of clinical magnetic resonance imaging (MRI) systems and their potential safety hazards preclude their use in student laboratories. Consequently, radiography students have traditionally learnt MRI physics by textbook alone. We have developed a remote access benchtop MRI system that provides students with 24/7 access to experimental learning exercises. Students work their way at their own pace through a series of guided measurements and experiments that progress from basic magnetic resonance phenomena to imaging and contrast manipulation. Learning is assessed by formative barrier quizzes that ensure appropriate progression, contributions to guided online discussion of the experiments, interpretation of experimental results, evidence of exploration beyond the guided experiment, discussion of the relevance to clinical imaging, and critical reflection on the learning experience. Initial student feedback on the experimental MRI learning experience has been positive in regard to the learning objectives of developing both a theoretical and practical understanding of MRI theory. The majority of student criticisms relate to the technological aspects of delivery of a remote access laboratory.

Introduction

Increasing clinical use of magnetic resonance imaging (MRI) has led to the demand for teaching the basic foundation of MRI theory in radiography courses. In Australia, MRI accreditation is provided by the Australian Institute of Radiography at two levels. Level 1 certification currently includes an examination covering basic MRI theory (AIR, 2014). Of all the medical imaging modalities MRI is the most versatile, but the underlying physics is also the most complex and conceptually difficult. This presents both learning and teaching challenges that are heightened by the usually very limited physics background of the students and the often short curriculum time allocated for covering MRI topics. Learning objectives in undergraduate radiography courses typically require only a basic understanding of MRI physics, while postgraduate qualifications aim for a deeper understanding. Learning objectives rarely include higher level thinking skills such as ‘apply’, ‘manipulate’, or ‘interpret’, because the complexity and expense of clinical and laboratory MRI systems generally precludes a hands-on learning experience. The extremely high magnetic fields of conventional MRI systems also present potential safety issues (Shellock, 2015), and necessitate both restricted access and very close student supervision.

The difficulty of access to MRI systems for laboratory learning exercises means that basic MRI theory has traditionally been taught exclusively by description alone. Despite the availability of a huge number of MRI texts and online learning resources our experience over six years at the University of Sydney is that learning outcomes for students using exclusively explanatory learning resources were mostly poor, falling well short of the learning objectives. The majority of students presented written work that indicated a confused understanding of the basic physics of magnetic resonance. Due to their failure to grasp the basics, the understanding of all higher and consequent concepts was also often confused. These difficulties were exacerbated by the presence of inaccurate and misleading theory in some of the most popular introductory MRI texts.

In 2009 we acquired a benchtop MRI system with the intention of providing our students with a hands-on experimental learning experience of MRI theory. This system (Magritek Terranova, http://www.magritek.com/products/terranova/) is much less expensive than a conventional MRI system because it uses the Earth's magnetic field rather than a superconducting electromagnet. The sensitivity of the device is very much lower than for a high field system but it nevertheless enables experimentation covering a wide range of magnetic resonance principles and imaging at low spatial resolution. The Terranova system, together with an accompanying Student Guide provided by the manufacturer, were specifically designed for learning the basic principles of magnetic resonance phenomena and MRI. Importantly, the Terranova software provides education-specific data displays that are not available on clinical MRI systems.

In order to learn MRI theory thoroughly, ideally each student would have unlimited access to an MRI system to perform basic physics and imaging measurements as well as experiments with artificial samples ('phantoms' in MRI parlance) and human subjects. This ideal is practically and financially impossible as well as ethically untenable. It is not reasonable to purchase multiple instruments that are used for only a short time by each student, require expensive maintenance and supervision, and may be susceptible to both intended and inadvertent damage by users. Thus, the preferable option is to provide controlled remote access.

The idea of remote labs evolved as a solution to the issues related to hands-on MRI experience. Remote laboratories allow users to perform experiments and laboratory tasks over the Internet without being near the actual equipment. In a traditional proximal laboratory (Figure 1), the user interacts directly with the equipment by performing physical actions (e.g. manipulating with the hands, pressing buttons, turning knobs) and receiving sensory feedback (visual, audio and tactile).

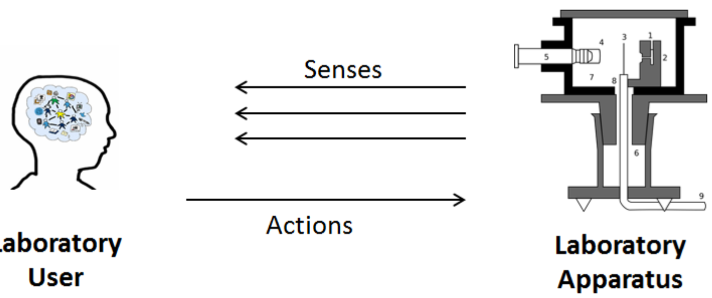

Figure 1. In a traditional proximal laboratory, the user interacts directly with the equipment.

In the case of an MRI learning laboratory, the apparatus is controlled by a computer (Figure 2), the 'patient' is an inanimate water or oil-containing object, and the sensory feedback is almost entirely visual. There are no moving parts and the only physical interaction required by the user is to occasionally change the object on which the experiments or measurements are performed.

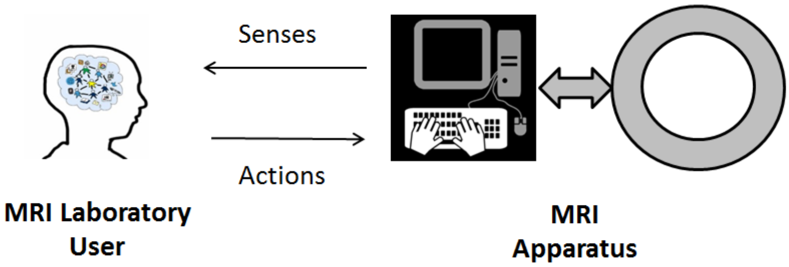

Figure 2. In a proximal MRI laboratory, the user interacts with the equipment via a computer.

While experimenting with a Terranova system is undoubtedly a fantastic experiential learning exercise for a committed individual student, we found it was not suitable for a conventional laboratory or practical class learning exercise. The delicacy of the system means it is unsuitable for unsupervised use and its low sensitivity means measurements are often quite slow and time consuming. For all students to be able to use the system we needed to control access and increase the range of times the system was available.

The 'Labshare' environment developed at the University of Technology Sydney (http://www.labshare.edu.au) provides a paradigm for multi-institution remote access to any computer-controllable laboratory apparatus (Lowe et al., 2009). Although it was originally developed for engineering teaching laboratories, we adopted Labshare to provide remote student access to the Terranova MRI system and, more recently, to a clinical computed tomography scanner (http://sydney.edu.au/health-sciences/netrad).

In a remote laboratory, interaction with the apparatus takes place at a distance through the remote interface (Figure 3). This is a new layer that sits between the user and the laboratory equipment. It is responsible for conveying user actions and receiving information from the equipment. Because the MRI apparatus is controlled by a computer and user interaction is almost exclusively visual in any case, the user experience is minimally affected by a lack of physical interaction with the apparatus compared with a proximal MRI laboratory experience.

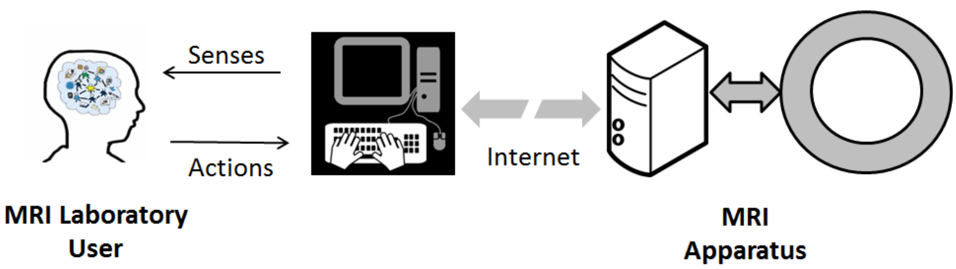

Figure 3. In the remote MRI laboratory, the user interacts with the equipment via a computer and the Internet.

The potential advantages of a remote access laboratory over a conventional proximal lab may include, but are not limited to: flexible access over extended hours; user safety; equipment security; decreased maintenance costs; and cost sharing (Abdulwahed & Nagy, 2013; Abdulwahed, Nagy, & Blanchard, 2008; Cartwright, 2000; Cooper, Donnelly, & Ferreira, 2002; Corter, Esche, Chassapis, Ma, & Nickerson, 2011; Makasiranondh, 2011; Nedić, Nafalski, Machotka, & Göl, 2011; Sharafutdinova et al., 2013; Trevelyan, 2003). In many laboratory classes students work in groups to use sophisticated equipment. While the group work potentially develops communication skills and encourages the exchange of ideas, the lack of individual access to the equipment limits each student's opportunity for direct experience.

Study Context

In the Discipline of Medical Radiation Sciences at the large institution in this project, basic physics of MRI is taught in Bachelor, Graduate Entry Masters, and Specialist Masters courses. The long-term pedagogic aim is to include some practical MRI experience in all of these courses. At present the use of the remote access system is restricted to one unit of the distance-only mode Specialist Masters course, which is the only unit that focuses solely on MRI theory. Typical enrollment is 30-40 students for the single semester unit that is offered once per year. The majority of enrolled students are full time radiographers pursuing professional development. The working hours of the students strongly affect usage patterns of the remote access system. The development of the remote access MRI system has enabled these students to obtain practical MRI experience without the need to attend local workshops.

Results and Discussion

Development of the NetMRI System

Magnetic resonance and MRI experiments with the Terranova system involve a series of measurements performed on several different samples (bottles containing liquids with different magnetic resonance properties). Normally these would be inserted into the device manually. For the remote access system we built a software-controlled 'robot' that can insert any one of four samples into the MRI device (Figure 4). The complete system: resonator, spectrometer, sample selection robot, control computer, and remote access server is designated the 'NetMRI' system.

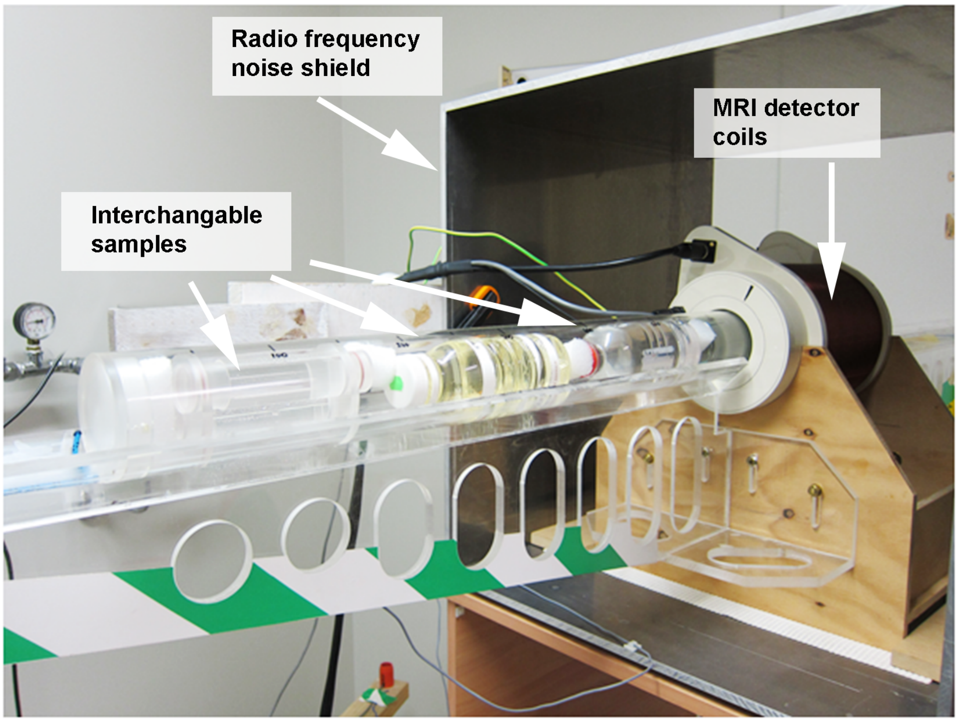

Figure 4. Hardware components of the NetMRI system. The computer and spectrometer are not visible in this image.

When a student logs in to the Labshare server she is presented with links to the remote devices (designated ‘Rigs’ by Labshare) to which she has access, together with their current status (Available; In use; Off-line). The student can use a calendar to make up to two 2-hour reservations. The Labshare server automatically makes time zone adjustments according to the location of the student’s computer. When the student connects from Labshare to the NetMRI system she is presented with a virtual desktop, as if she were sitting at the computer in front of the Terranova, but with access to only specific software - in this case the control for the Terranova and the control for the sample robot. There is no access to the operating system or other software. For some remote access laboratories, a webcam can provide a video feed that shows the behaviour of the apparatus. We have not provided this for NetMRI because physical movements occur only when the robot changes the sample. To enhance the authenticity of the remote access experience, prior to their experiments students are given a guided tour of the apparatus in an online video presented by the academic in charge. This video also emphasises the distinction from a simulation environment.

In order to connect to and operate a remote device through Labshare, the student’s computer must run VPN (virtual private network, a university ‘firewall’) and Java. Depending on the remote device and the type of data display and system control, the remote control experience may be compromised by the bandwidth of the Internet connection. For NetMRI this has been an issue for a few students in rural areas with poor Internet speeds.

Learning Resources

Learning of MRI theory using the NetMRI system is supported by a range of learning resources:

- An introductory video in which the teaching academic shows and describes the various parts of the NetMRI hardware.

- A video showing how to login to the Labshare system, make a rig reservation, and connect to the MRI rig.
- Eleven 5-10 minute YouTube videos on basic MRI theory presented by Sir Paul Callaghan, a world-leading MRI theory expert (https://www.youtube.com/user/magritek). These include demonstrations using the Terranova system.
- A Student Guide describing MRI theory and corresponding practical experiments to perform on the NetMRI system. This guide (provided by the Terranova MRI manufacturer) has been edited by the teaching academic to account for the remote access paradigm and to remove some theoretical detail.
- Walkthrough videos outlining each of the first few experiments and the type of signal quality to expect. This is particularly important for our NetMRI system because the local environment is noisy and the signal quality is poorer than that shown in the manufacturer's Student Guide illustrations.
- Recommended textbook readings to supplement the theory presented in the Student Guide.
- An online moderated discussion board for students to present experimental data and seek help.

Figure 5 provides a schematic illustration of the module content and learning workflow.

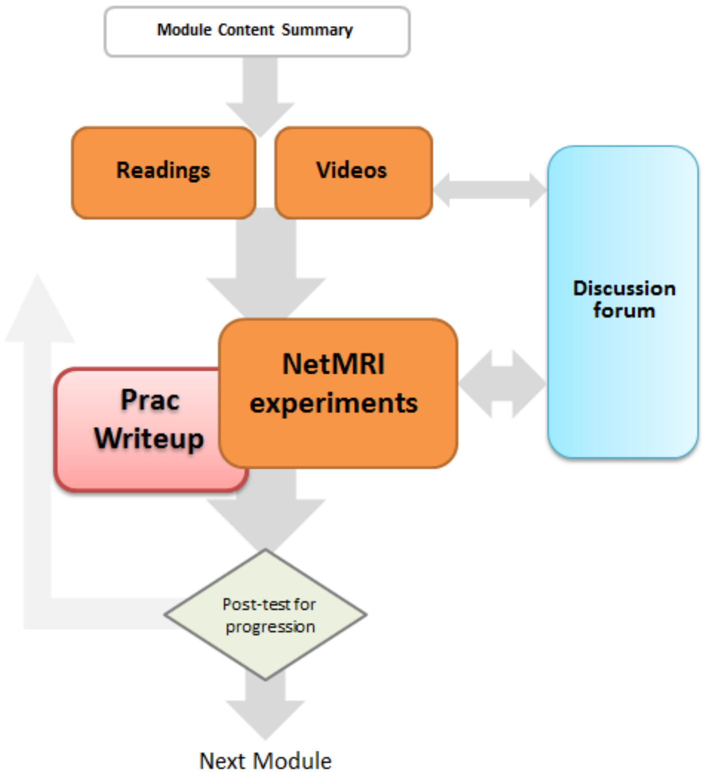

Figure 5. Schematic diagram showing progression of learning module content.

Assessment of Learning

Assessment is based on an individual student's achievement of the following Learning Objectives, taken directly from the Unit of Study outline:

- Demonstrate a theoretical and *practical* understanding of the process of MRI signal acquisition.
- Understand, *measure* and *analyse* basic MR parameters including T_1 and T_2.
- Understand and *perform* 1D and 2D imaging measurements and *optimize* acquisition parameters.
- Understand and *manipulate* image contrast by *adjustment* of acquisition parameters.
- Understand the effect of noise on imaging and *adjust* imaging parameters accordingly.

The higher order objective descriptions have been italicized for emphasis. These demonstrate our aim to provide a learning experience that translates to the professional aspirations of the students and goes beyond what can be achieved from textbooks and lectures.

We have implemented a range of assessment methods that are designed to act as learning guides rather than performance hurdles. An important component of assessment is the students' use of conventional MRI terminology. This is not learning jargon for its own sake. In their professional practice, graduates from the course must be able to communicate efficiently and unambiguously with their colleagues. Many of the assessment tasks require such written communication and so permit assessment of communication skills.

The following headings describe the formative and summative assessment tasks and relative mark weightings. The proportion of the total 'MRI Theory' unit mark allocated to practical exercises using the NetMRI system (45-80%) has varied from year to year as the pedagogical model has evolved.

Formative barrier quizzes that ensure appropriate progression. (No mark)
The practical learning exercises are presented in three modules. To ensure that students have the required knowledge and skill level for the exercises in the second and third modules, a formative online multiple choice quiz must be passed to progress from modules 1 and 2. This quiz requires *application* of the most important theory topics and expert *interpretation* of screenshots of data acquired in the current module experiments. There are no quiz questions that are simple tests of memory. These barrier tests are important in ensuring efficient use of the remote access system. Because most students require multiple 2-hour sessions to complete each module, attempts to perform the experimental exercises without adequate preparation and background knowledge are likely result in slow progress and ineffective use of reservations.

Contributions to guided online discussion of the experiments. (5% of prac mark)
An online moderated discussion runs in parallel with each experimental module. In the discussion, students post questions about their experiments and the academic in charge monitors the responses from other students. Marks are awarded for active, accurate, and constructive contributions to the online discussions. It is not expected that every student will contribute to every discussion topic. The moderator intervenes when MRI theory or practice errors are not corrected in the students' discussion, preferably by indicating that there is a problem and guiding the responses towards a correct understanding rather than making explicit corrections. Students mostly engaged well with this task and many specifically mentioned the value of the online discussions in end of semester survey responses.

The moderator also posts a series of 'spot the textbook error' discussion topics. These are illustrations from MRI textbooks that are misleading and/or inaccurate. The purpose of these topics is to emphasise to students the importance of assessing the reliability of any learning resource by research and cross-validation.

Interpretation of experimental results. (50% of prac mark)
The Student Guide comprises eleven chapters that present important magnetic resonance theory followed by a suggested series of experimental measurements that illustrate the theory. To a certain extent our NetMRI system throws students in at the deep end because the Earth's field device is significantly affected by electromagnetic noise in the local environment and by a small but erratic drift in the ambient magnetic field strength at our campus (due to electric trains). These external but real factors mean that every measurement is likely to have a different value. The student must interpret their results taking into account these external factors and, if necessary, making adjustments to the way the measurement is performed to reduce their influence. Students are assessed on their ability to interpret their results in terms of magnetic resonance theory rather than the presentation of a specific result. It is not sufficient to simply perform and report a measurement. The student should demonstrate an ability to critically assess the quality of the data and the reliability of the result, and make theoretically sound hypothesis about deviations from expected results. Learning to discriminate noise from expected signal and being able to make compensating adjustments to methods is a critical skill in MRI.

Evidence of exploration beyond the guided experiments. (15% of prac mark)
Magnetic resonance imaging is an extraordinarily powerful technique because there are a large number of experimental parameters than can be manipulated to produce signals that are dependent on a wide range of physical properties of the imaged object. In medical imaging this translates to being able to image both structural and functional properties of tissue. The Student Guide to experiments covers the essential theory and the student operator of the NetMRI system has control over a wide range of experimental parameters (an example is presented in Figure 6). Students are encouraged to explore beyond the basic required experiments, and marks are awarded for evidence of exploration and discussion of results in terms of MRI theory.

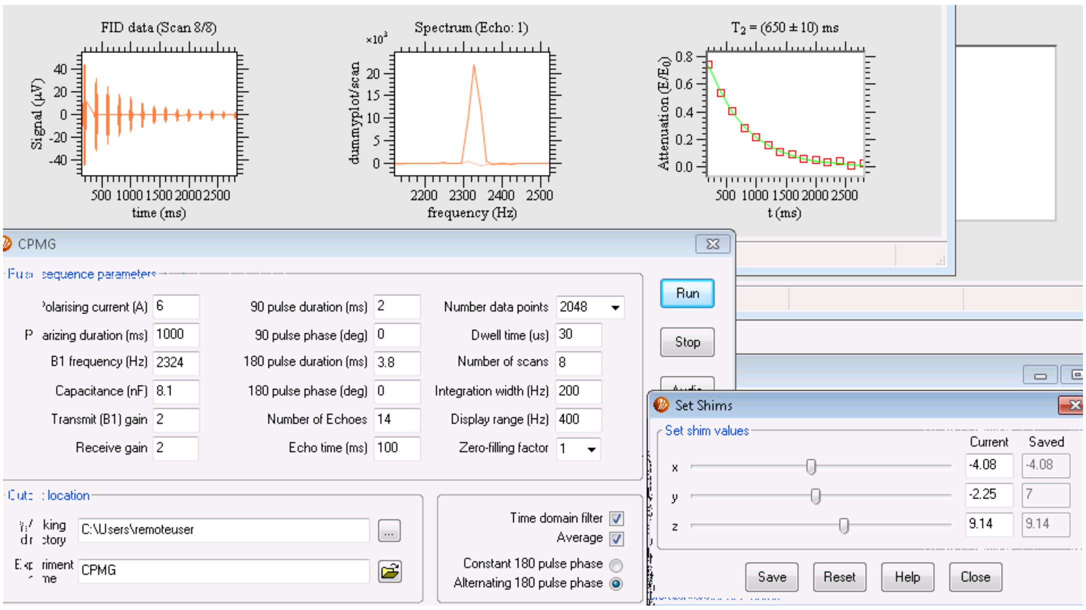

Figure 6. Example of the experimental interface. In this experiment there are up to 24 independent user-controllable acquisition parameters ('CPMG' and 'Set Shims' windows) that may affect the measurement results (top three images).

An example of performing meaningful experiments beyond those described in the Student Guide would be reporting data and its interpretation from a series of measurements performed to assess the effect of a parameter modification. Only about 10% of students presented significant evidence of performing any experiments not described in the Student Guide. A possible explanation for this is that many students reported difficulty in completing the standard Student Guide experiments in the available time for which they could reserve the system (there is a 2-hour limit for any single reservation and only two reservations are permitted until at least one is used). A proposed change from the Earth's field system to a higher field strength permanent magnet MRI device will simplify and expedite measurements and we hope increase the desire and ability of students to engage with this exploratory aim.

Discussion of the relevance to clinical imaging. (20% of prac mark)
The students in our current MRI Theory course are mostly qualified radiographers seeking specialist training in order to work in MRI. Some are already working in MRI departments but without a specialist certification. Although this is primarily a physics course it is important that students are able to recognize the relevance to clinical practice and marks are awarded for discussion of the theory as it is used in clinical imaging techniques.

This assessment criterion was useful in identifying students that were able to contextualize their learning in their actual or intended professional practice. It also highlighted the level of students' understanding of the technical and operational differences between the very low magnetic field strength Earth's field MRI and a high field superconducting clinical MRI scanner.

Critical reflection on the learning experience. (10% of prac mark)
Ten per cent of the total practical marks are awarded for a short reflection on the student's learning experience. The aim of this assessment is to encourage students to consider the relative merits of the available learning resources and particularly to compare the remote access laboratory experiments with purely descriptive resources such as textbooks. The student reflections also provide valuable feedback for improvement of the remote access system in terms of technology, the experimental learning exercises, and the method of assessment.

Student reflections in this section were diverse, ranging from complaints about technical access issues to encouragement of professional colleagues to enroll in the unit. Many students felt the learning experience was frustrated by the technical aspects of setting up their computers to work with the remote access system. This highlights the need to provide support resources including documentation and contact information for university computer support for students less familiar with computer systems. Many students commented on the value of being able to 'change parameter settings and see what happens' and how this enhanced their understanding of MRI theory. Interestingly, some students used this section to describe experiments they would have liked to perform had sufficient time been available. The alignment of such proposals with the learning objectives provided a further indication of the student's actual learning outcomes.

Limitations of the Earth's Field MRI System
Student criticisms of the NetMRI learning experience related primarily to technical access issues. Although the rig was available for use 24/7, the students enrolled in our distance education course mostly work full time and therefore prefer to use the system in the evenings

before midnight and on weekends. Because we have only one MRI rig available, this led to many students having difficulty gaining enough access sessions to complete the full range of experiments described in the Student Guide. In contrast to the engineering rigs for which the Labshare environment was initially developed, the MRI experiments are time-consuming and complex, requiring around 20-40 hours total access time for most students. We are addressing this problem by replacement of the Terranova system with a permanent magnet system (http://www.pure-devices.com), which is less complex to operate, and, due to much higher signal strength, requires less time for measurements. In the long term it is hoped to provide multiple MRI rigs to alleviate access conflicts.

A software problem in the reservation system meant that students sometimes lost their reservations unexpectedly and were unable to access the NetMRI. When some students had taken leave from their work to perform their online experiments this was obviously a major frustration that added stress and detracted from the learning experience. Recent analysis of the reservation system has identified ways of reducing student loss of access through a better description of how the reservation system works and refinement of the reservation system parameters.

Despite having privileged access to cutting-edge learning resources, students have high expectations for functionality and are easily frustrated by technical and access problems. Students expect that the remote access paradigm will be similar to a more familiar proximal laboratory experience and that the technology mediating the connection to the remote system will be invisible. Although not all technical problems can be foreseen it is extremely important to test any system as much as possible and to provide comprehensive instructions for the process of connection to the remote laboratory together with clear reliable access to technical support.

Limitations of this study

This paper describes our initial experience with a remote access MRI learning laboratory over a three-year period of introduction and development of both the system and the assessment methods. Our reported observations are based on informal student feedback gathered from a variety of sources rather than a formal survey specifically designed to assess the student learning experience. A formal survey is currently in progress and is focused on obtaining student impressions of the relative merit of remote laboratory versus textbook learning of MRI theory.

Conclusions

A remote access laboratory has the potential to provide students with an immersive learning experience that achieves higher order learning objectives, including analysis of real world data, experimental design, and hypothesis testing. For some types of laboratory apparatus, for example the MRI system described here, remote access is not a poor alternative to a proximal 'hands-on' laboratory activity but the only safe and viable means of providing interactive access to dangerous, delicate, and expensive apparatus. Remote access does not appear to preclude the assessment of thoughtful and constructive communication between students. An online discussion may reduce students' sense of isolation, supplement online and offline learning resources, establish a learning community, and present a method of assessment of communication skills. In our experience, student expectations for the remote access user experience are very high and particular attention needs to be paid to supporting the mediating technology and adapting the learning activities to the remote access paradigm.

Acknowledgements

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