An Inexpensive Laboratory Module to Teach Principles of NMR/MRI

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Abstract

We report the details of, and our experience with, a relatively simple and inexpensive teaching laboratory apparatus which demonstrates some of the basic physical phenomena and principles of Nuclear Magnetic Resonance (NMR) and Magnetic Resonance Imaging (MRI). Our approach uses two 2x2x1 inch Neodymium Iron Boron (NdFeB) permanent magnets in the 0.6 T range, and large cylindrical (5 inch diameter, one inch thick) field-spreading pole pieces made of soft steel, along with a one-half-inch-thick walled soft-steel enclosure. This design trades away field strength for uniformity in order to get a large enough volume (at least a 1 cm cube) of highly-uniform 0.08 T in which the NMR phenomenon is easily observed.

While others have demonstrated and/or market more complex and elegant benchtop NMR or MRI systems generally costing several thousands of dollars (e.g. TeachSpin®), our goal was to create a simple tool which would be inexpensive enough so that there could be one per lab bench in an imaging course. The magnetic field is also well contained in this design, and not strong enough to represent a significant hazard or nuisance. The component cost (including magnets) for this system is approximately $400 and it can demonstrate Free Induction Decay and Spin Echo. The sample used can be a small container of glycerin. It is assumed that an oscilloscope and a bench power supply are available.

This module is was used in the form of a lecture demonstration of the Spin Echo experiment in the Northwestern University Biomedical Engineering course BME 325, Introduction to Medical Imaging, during the Fall 2004 quarter. This course includes undergraduate and graduate students from both ECE and BME majors. We report our experiences and a formal evaluation of the effectiveness of the module.

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Introduction

Magnetic Resonance Imaging (MRI) is one of the most important medical imaging modalities, yet it is also the least intuitive. Other modalities, such as x-ray, ultrasound, radionuclide methods are relatively easy to visualize, even in tomographic forms. MRI, on the other hand, relies on subtle behavior of matter which is not encountered elsewhere in most students' lives.

Laboratory exercises and demonstrations are useful for building an intuition about such physical principles. Commercial MRI and NMR systems, however, are relatively expensive and therefore difficult to incorporate in a teaching laboratory. The goal of this project was to develop a low-cost system which could demonstrate the Spin Echo experiment.

Previous Work

Others have developed desktop NMR and MRI systems for teaching or research use. Wright, et al. [1] developed a complete desktop MRI system with a 2.5 cm imaging region and 0.21 T field strength. The estimated cost of this system was $13,500. Kirsch [2] describes the electronic circuitry for demonstrating pulse NMR, including spin echo, although details of the magnet are not given. A commercial system is manufactured by TeachSpin, Inc. for demonstrating pulsed NMR phenomena, with a list price of $13,850.

Apparatus description

To reduce costs we developed a simple magnet system which achieves a 0.08 T field with adequate uniformity over a 1 cm^3 volume. The field originates in two 2x2x1 inch NdFeB permanent magnets having a field strength (on the 2x2 face) of approximately 0.6 T. The magnetic circuit uses a rectangular box made of 0.5 inch thick ASTM A-36 hot rolled steel, built using two 10 inch and two 6 inch, plates, each 6 inches wide. The permanent magnets are affixed within the box opposite each other across the short dimension. On each magnet is placed a 5-inch round, 1-inch thick cylinder pole piece of hot-rolled 1018 steel, resulting in a 1.75 inch gap between the poles. In this arrangement many of the field lines originating at the permanent magnets are shunted directly around and wasted, but the field within the gap is highly uniform, especially at the center. Small NdFeB magnets (3/8 inch square, 1/8 inch thick) are placed on the rears of the pole-piece cylinders to shim the field and attain the highest possible uniformity. Aluminum foil is used around the outside of the box for RF shielding to improve signal quality. Figure 1 shows the magnet system, with the RF coil in place.

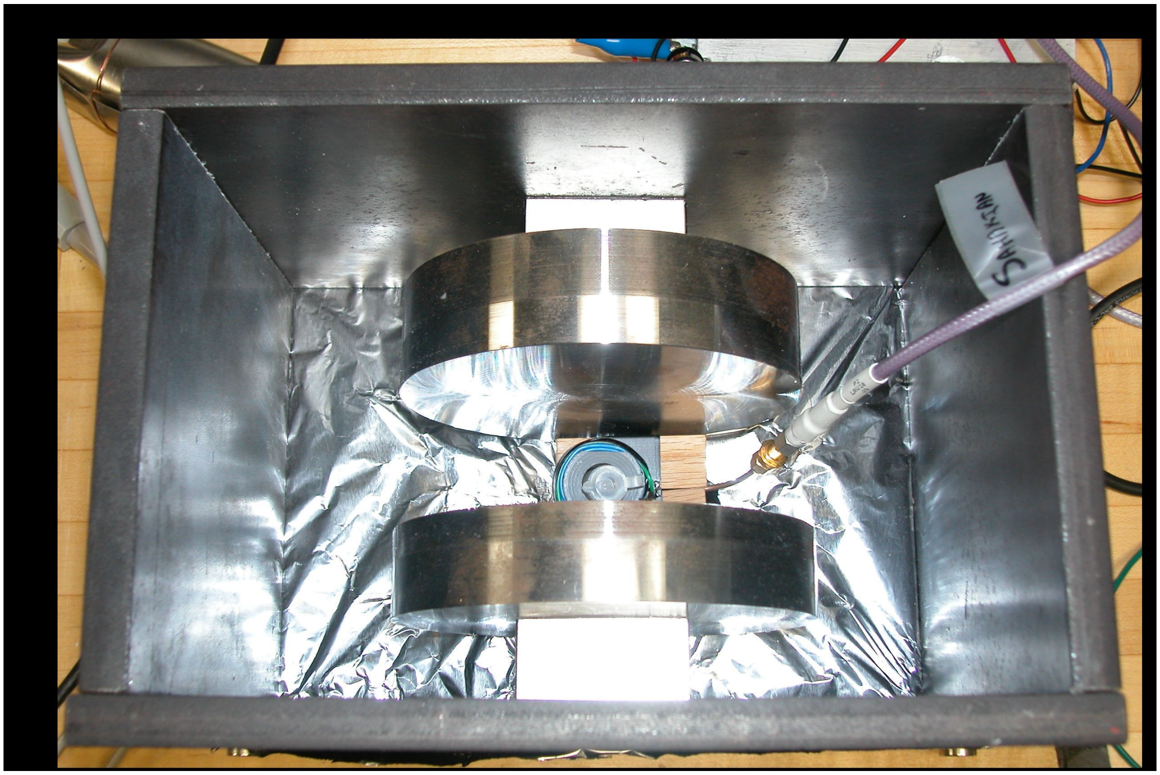

Figure 1. The magnet system and the RF coil in place.

The Larmor frequency (for protons) for this magnet is 3.38 MHz, making the RF circuitry relatively inexpensive. The electronic circuitry is straightforward, using Minicircuits mixers, RF switches and power splitters, and an Avantek preamplifier (50 dB gain, 3.5 dB noise figure) and power amplifier (30 dB gain, 1 W output), in a configuration very similar to Kirsch's [2]. The initial 90 degree flip and 180 degree refocusing pulses are generated using simple 555 timers, with pulse widths of 17.5 and 35 μs and an inter-pulse interval of 1.4 ms. A lab signal generator, power supplies are used to operate the circuits and a high-sensitivity oscilloscope are used to view the received signal. The RF coil is simply a 60-turn coil of solid 20 gauge copper wire with a diameter of 1 inch and length of 1.5 inches wound around a PVC cylinder with a 0.5 inch bore for the sample. A 50 Ω feed point at LC resonance is achieved using one fixed and one variable capacitor in series across the coil. A small cylinder containing glycerin is used as a sample.

With this apparatus, once the frequency is properly adjusted, the oscilloscope displays the classical spin echo stimulus and response pattern. The first (90 degree) RF pulse is followed with the exponential free-induction decay and the second (180 degree) RF pulse is followed by the echo of the refocused spins after the appropriate delay. Figure 2 is a captured screen shot from the oscilloscope showing a typical result. Although we did not incorporate a third pulse in this initial version of the apparatus it would be an easy matter to do so to view the decline in the amplitude in subsequent echoes due to the T2-related (spin-spin) decay.

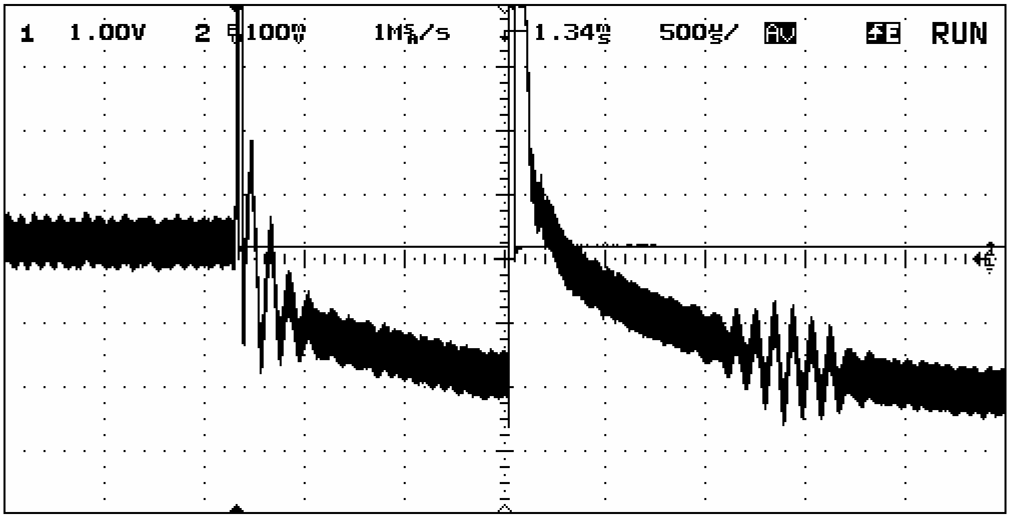

Figure 2. A captured oscilloscope display of the spin-echo experiment with the apparatus described. The first RF pulse (90-degree flip angle) is delivered at the center of the left half of the screen and is followed immediately by the free-induction decay signal. The second RF pulse, (180-degree flip angle) is centered on the screen, and results in the re-focused spin echo seen at the center of the right half of the screen. Eight repetitions were averaged for this display.

Evaluation

The apparatus was demonstrated in the course BME 325, entitled "Introduction to Medical Imaging," during the Fall 2004 quarter. This course includes undergraduate and graduate students from both Electrical and Computer Engineering (ECE) and Biomedical Engineering (BME) majors. Students in this course had learned about the NMR and MRI concepts during the quarter prior to the demonstration. The aim for the demonstration was to make the NMR and MRI concepts visible to students in such a way that would help them to better comprehend the physical phenomenon and the principles associated. The effectiveness of the designed apparatus and its demonstration was assessed through asking students to reflect upon the presentation. Students' perspectives were explored to evaluate the effectiveness of the demonstration. We report the study context--the demonstration--, and its effectiveness for the targeted population as how it was informed from students' reflections.

Study context: The NMR demonstration.

The present demonstration was done in a typical classroom rather than a laboratory. Though we do not simply claim that it is always feasible to conduct an NMR/MRI experiment in a typical classroom rather than a laboratory, in our case, it was more convenient for us to bring the apparatus to the classroom rather than moving students to a laboratory. The apparatus was transported to class on a cart and was placed in front of students, close to the blackboard, where the instructor often stands while he lectures.

Even though the class size was modest (18 students), students who were not sitting in the first row would not be able to see the details of the apparatus and follow the instructor. Locating students close to the apparatus and showing the components would have been inconvenient because it was hard for more than a few people to actually stand next to the apparatus and follow the demonstration effectively. One way could be grouping students of two to three, and showing the demonstration one by one. However, the demonstration lasted for almost the entire 50-minute class meeting time and within the already overly crowded curriculum, using more than one class meeting time is undesirable. Therefore, the class instructor used a small video camera while he was leading the presentation. The camera was connected to a projector making the images easy to follow for the students sitting in class even in the farthest seat. Prior to the presentation a handout representing the schematic diagram of the NMR apparatus was distributed to students in class. The instructor briefly summarized the components of the NMR apparatus and their functions. In this summary, each component and the associated parameters in relation to other components were described. The instructor simultaneously projected the camera toward the components he was referring to. Each component was shown one-by-one, its function and relation to the other components were stated.

Evaluation instrument

To explore the effectiveness of the NMR demonstration, we designed an NMR demonstration student questionnaire. The questionnaire comprised four items written in Likert-scale and open-ended type.

The first item was intended to assess the extent to which students think the NMR demonstration a) made the listed concepts <u>visible</u> to them and b) helped them to <u>better understand</u> these concepts. This item was designed as a matrix, with a five point Likert-scale, 1 to mean "not at all" and 5 to mean "to a great deal" responses. The concepts listed in this matrix were a) the meaning and calculation of Larmor Frequency, b) RF pulses and flip angle, c) 90° RF pulse and free induction decay, d) 180° refocusing pulse and the spin echo, e) the measurement of T2, f) Bayesian equations, and g) other. The concepts from (a) to (e) were the five main concepts the MNR demonstration intended to explicate. Even though the "Bayesian equations" concept, (f), was neither explicitly nor implicitly embedded in the NMR demonstration, we listed it as another concept in the matrix likewise as a controlling variable. The average student rating of the Bayesian equations concept provided us a base line to make meaningful comparisons of the targeted concepts' ratings. The last concept, "other", (g), was included in the listed concepts in order for students to be able to inform us any concept that they visualized or better understood other than the aforementioned concepts we had listed.

The second, the third, and the fourth items were posed open-ended. The second item asked students how the NMR demonstration could be improved. This question helped us to identify the ineffective aspects of the demonstration that would eventually help us to improve the quality of students' experiences. The third item asked students to reflect upon the demonstration, and describe their experiences with it. Whether students liked the demonstration, found it interesting, thought that it would be helpful for them to better understand the concepts, etc. were the unit of analysis for this item. The last and the fourth item asked students if they were willing to help improve the NMR apparatus or an associated lab experiment. We posed this question to further recruit student volunteers for efforts to design other experiments utilizing the NMR demonstration apparatus.

Participants

Eighteen students all of whom were in class during the NMR demonstration were the study participants. These student participants constitute a self-selected group; we purposively select them because they were the group of students enrolled in "Introduction to Medical Imaging" course at the targeted university during the Fall 2004 quarter. Students were from ECE and BME departments in both graduate (7) and undergraduate (11) levels.

Data collection

After the NMR demonstration and student-initiated discussions were completed, we administered the NMR demonstration student questionnaire. We explained to students our purpose of administrating the questionnaire. We assured students that their responses would only be used for research purposes--to improve the effectiveness of the demonstration--, but not in any aspect of students' course grades or their other departmental credentials. When the class first met in the beginning of Fall 2004 quarter, we had introduced our interest to collect data in their classes. Thus, the students were already informed about the Institutional Review Board regulations and the consent forms as well as their rights as participants. All the students in class have chosen to voluntarily participate in the studies we proposed them to conduct and they consented us to utilize their responses.

Findings

The NMR questionnaire data revealed that students found the demonstration helpful to make the selected concepts become visible to them (Figure 2). Students reported that the NMR demonstrations helped them to visualize the "90° RF pulse and free induction decay" and "180° refocusing pulse and the spin echo" concepts mostly. The average student ratings for these two concepts was 4.8, indicating that students thought the demonstration helped to visualize them at a great deal. The next second highly rated concepts were the "RF pulses and flip angle-visible" and "Larmor Frequency." The average ratings for these concepts were respectively 4.5 and 4.3, indicating that students thought the demonstration helped to visualize them a great deal. Students rated "the measurement of T2" concept as somehow became visible to them, with a rating of 3.6. The "Bayesian equations" concept was rated low. The average student rating was for this concept was 2.5, which is below 3, indicating that students thought this concept was not made visible to them through out the demonstration.

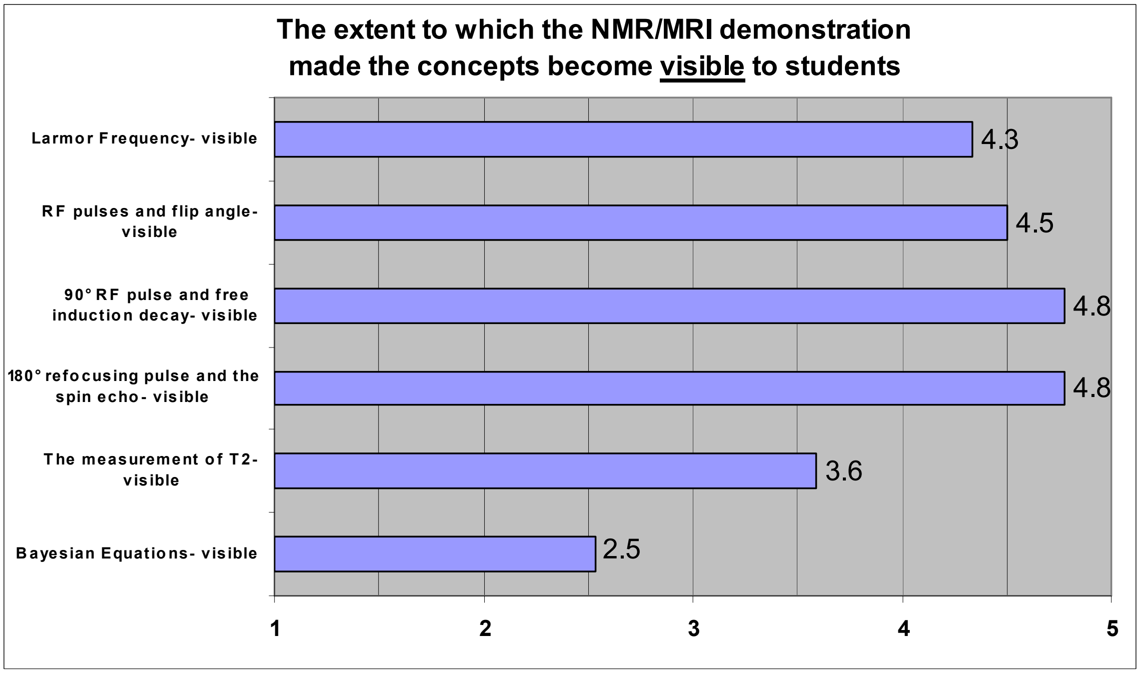

Figure 2. The NMR/MRI concepts and the extent to which these concepts become visible.

In Figure 3, the average scores of student rating (4.6) for the "90° RF pulse and free induction decay" and "180° refocusing pulse and the spin echo" concepts indicate that these concepts were the most understood in the demonstration. "RF pulses and flip angle-visible" and "Larmor Frequency" concepts were the next highly rated concepts with average scores of 4.4. and 4.1. Students rated "the measurement of T2" concept as the fifth mostly understood concept with a rating of 3.7. This concept was rated different than other concepts; for all the listed concepts, better understanding scale was rated slightly less than the visibility scale, though for "the measurement of T2" this was the exact opposite.

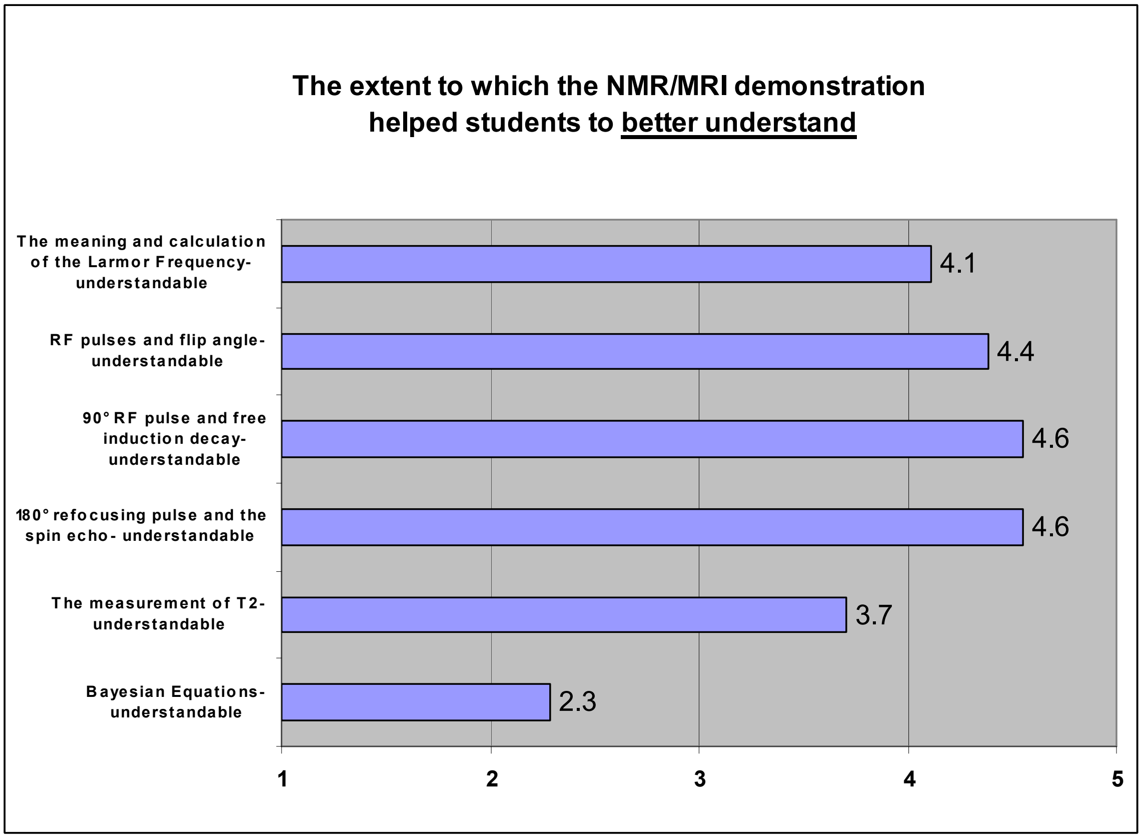

Figure 3. The NMR/MRI concepts and the extent to which students think they better understand them.

The analysis of the open-ended questionnaire items revealed that almost all students liked the demonstration and found it interesting. Approximately 90 percent of student participants indicated in their responses that the NMR demonstration was helpful for them to visualize the related concepts. 80 percent of those respondents reported that they understood the related concepts better. 22 percent of the respondents were willing to provide help to improve the apparatus and/or to design an associated lab experiment.

Conclusions

The simple NMR apparatus and demonstration described forms an effective tool for improving student understanding of the relatively abstract physical effects at the heart of MRI. This apparatus is inexpensive enough to have one per bench in a teaching laboratory.

Appendix A: Questionnaire

Nuclear Magnetic Resonance (NMR) Demonstration
Student Questionnaire

Directions: Please help us to explore the effectiveness of the NMR demonstration you have observed, by completing this student questionnaire. Your responses to the questionnaire items are confidential: only the researchers will have access to them and they will only be used to improve the effectiveness of the NMR demonstration. Your course grade or other credentials in your program will not be influenced because of your responses. Thanks for your help.

1- NMR demonstration was designed to make the relevant concepts visible to you that are difficult to visualize otherwise. The ultimate objective is for you to better understand the NMR concepts. In the following matrix, please indicate the extent to which you think the NMR demonstration: (a) made the concepts visible to you and (b) helped you to better understand these concepts. Circle the appropriate number for each of these concepts, using 1 to mean "not at all" and 5 to mean "helped a great deal."

	The extent to which the NMR demonstration;									
Concepts	(a) made the concepts become **visible** to me.					(b) helped me to **better understand.**				
a- The meaning and calculation of the Larmor frequency	1	2	3	4	5	1	2	3	4	5
b- RF pulses and flip angle	1	2	3	4	5	1	2	3	4	5
c- 90^0 RF pulse and free induction decay	1	2	3	4	5	1	2	3	4	5
d- 180^0 refocusing pulse and the spin echo	1	2	3	4	5	1	2	3	4	5
e- The measurement of T2	1	2	3	4	5	1	2	3	4	5
f- Bayesian equations	1	2	3	4	5	1	2	3	4	5
g- Other (please note it): ____________	1	2	3	4	5	1	2	3	4	5

2- How can the NMR demonstration be improved?

3- What is your overall experience with the NMR demonstration? (e.g., Do you think the demonstration was important/unimportant?, Did you like/dislike it? Would you be interested in using the demonstration apparatus in a lab experiment? Do you think the demonstration has potential to help students better understand NMR/MRI concepts? Why or why not?)

4- If you are asked to provide help to improve the NMR apparatus and/or to design an associated lab experiment, would you be interested in volunteering? If you do, how would you like to contribute?

References

[1] S.M.Wright, D.G.Brown, J.R.Porter, D.C.Spence, E.Esparza, D.C.Cole and F.R.Huson "A desktop magnetic resonance system," Magnetic Resonance Materials in Physics, Biology and Medicine, v.13, pp. 177-185, 2002.

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Biographies

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CHRISTOPHER HAYES earned the MS degree in Biomedical Engineering at Northwestern University in June 2004. He had previously earned the BS in EE from Valparaiso University. He is currently a Field Engineer at Medtronic, Inc. (Minneapolis).

BUGRAHAN YALVAC is a Postdoctoral fellow in assessment studies for the VaNTH ERC at Northwestern University. He holds B.S. degrees in Physics and Physics Education and an M.S. degree in Science Education from METU, Ankara. For his Ph.D. studies at Penn State, he majored in Curriculum and Instruction and minored in Science, Technology, and Society (STS).