An active learning approach to education in MRI technology for the biomedical engineering curriculum

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ABSTRACT
It is challenging to give students an intuitive understanding of the basic magnetic resonance phenomenon and a sample of the many MRI techniques. Whereas compact mathematical descriptions of MRI techniques can be made, students are typically left with no intuitive understanding unless the common sense expressed in the math is in focus. Unfortunately, the nuclear dynamics happen in four dimensions, and are therefore not well suited for illustration on blackboard. 3D movies are more appropriate, but they do not encourage active learning. The typical solution employed by educators is hand waving (literally), since arm motions can to a limited extent be used to illustrate nuclear dynamics. Many students find this confusing, however, and students who do not grasp the meaning during lectures, are left in a bad position. For this reason, educational software was developed over the last decade (the Bloch Simulator). It is freely available and can be run directly from the software homepage that also links to YouTube software presentations aimed at educators and students who have already gotten a first introduction to MRI concepts. The software is mainly aimed at educators for interactive demonstration of MRI techniques but can also be used for student exercises which may significantly improve the understanding of MRI concepts. The presentation demonstrates software made for the first few minutes of MRI education but focuses mostly on the educational value of the more advanced Bloch Simulator. It is explored how, and to what extent, active learning based on the software may improve student understanding. An interactive teaching session on advanced topics (pulse types, the Fourier relationship, selectivity) was evaluated using pre- and post-lecture anonymous questionnaires. These are challenging and significant subjects, and it was hypothesized that the approach may improve student understanding considerably. Though rigorous testing of the benefit over traditional teaching was not within the scope of the project, indications of improved skills were found, and the student satisfaction was excellent.

Keywords – magnetic resonance imaging (MRI), education, evaluation, Bloch MRI simulator software

I INTRODUCTION

Magnetic Resonance Imaging (MRI) is an important part of the biomedical engineering curriculum. It is challenging, however, to give students an intuitive understanding of the basic magnetic resonance phenomenon and a sample of the many MRI techniques. Whereas compact mathematical descriptions of MRI techniques can be made, students are typically left with no intuitive understanding unless the common sense expressed in the math is in focus. The relevant nuclear vector dynamics happen in four dimensions, and are therefore not well suited for illustration on blackboard. 3D movies are appropriate, but they do not encourage active learning. The typical solution employed by educators is hand waving (literally), since arm motions can to a limited extent be used to illustrate vector dynamics. Students may find this confusing, however, and students who do not grasp the meaning during lectures, are left in a bad position.

For this reason, educational software was developed over the last decade (the *Bloch Simulator*, Hanson 2007). It is freely available and can be run directly from the software homepage http://www.drcmr.dk/bloch that also links to popular YouTube software presentations (Hanson 2011a) aimed at those who have already gotten a first introduction to MRI concepts. The software is mainly aimed at educators for interactive demonstration of MRI techniques but can also be used for student exercises and general exploration, which may significantly improve the understanding of MRI concepts.

This paper introduces software made for the first few minutes of MRI education (*JavaCompass*, Hanson 2011b) but focuses mostly on the educational value of the more advanced *Bloch Simulator* (Hanson, 2007). It is explored how, and to what extent, active learning based on the software may improve student understanding. An interactive teaching session on advanced topics (pulse types, the Fourier relationship and selectivity) was evaluated using pre- and post-lecture anonymous questionnaires. The session included group exercises where it was discussed how particular MRI techniques could be realized and visualized. The exercises were interleaved with class discussions where the ideas were tested using the simulator. The mentioned subjects are challenging and significant, and it was hypothesized that the approach may improve student understanding considerably. Though rigorous testing of the benefit over traditional teaching was not within the scope of the study, indications of improved skills were found, and the student satisfaction was good.

II CONTEXT

Engineering education is often not adequately engaging for all students. Teaching and learning styles are not sufficiently aligned, which can be improved by varying the teaching style (Felder and Silverman, 1988). Active learning approaches should be included in the portfolio of teaching methods to meet the needs (Felder *et al*, 2000) though this concept is so broadly defined that evidence for its efficiency is not solid in all cases (Prince, 2004). Teaching the Biomedical Engineering (BME) curriculum may be particularly challenging, since traditional engineering courses are mixed with more biological and medical courses (Harris, Bransford and Brophy, 2002). This likely improves occasional alignment with student interests and preferred learning styles over the education as a whole, but the expected added diversity of student preferences may broaden the range of needed teaching styles in the individual courses.

As part of the Medicine and Technology program at the Technical University of Denmark (DTU), a range of courses on medical imaging is offered, partly within the study line “Medical Imaging and Radiation Physics” (Wilhjelm *et al*, 2011). The students meet the different medical imaging modalities (e.g. CT, PET, ultrasound and MRI) at several courses (numbered 31500, 31540 and 31545) during the bachelor and early master study at increasing levels regarding depth of coverage and mathematical complexity. These courses described in the DTU study handbook (DTU, 2011), constitute a spiral curriculum, where teaching and task solving is performed at the highest level allowed by the limiting, but steadily growing, mathematical, physical and computational skills of the students. In this way, complex and relevant techniques such as MRI can be included early in the education which is both motivating and serves to push the boundaries of the students’ mathematical skills. Already after the first week of their university study, the students conduct a “dry lab” group exercise addressing the basic magnetic resonance phenomenon. The exercise is based on educational software available at http://www.drcmr.dk/JavaCompass. The page also links to the written exercise in Danish, and an early version of this in English. The students are later exposed to more complex subjects, visualized using software available at http://www.drcmr.dk/bloch

After the undergraduate courses, the students may choose the specialization course 31547, Medical Magnetic Resonance Imaging, which addresses the subject in much more detail, and which supplements prior experience with important applications, data acquisition at hospitals and data analysis exercises that are described in obligatory, short, individual reports (DTU, 2011). The course includes traditional lectures interrupted by frequent questions and answers. During the semester, pairs of students present new subjects within the course curriculum (learning-by-teaching, 10 minutes per student). Software for quantitative analysis of the acquired data is programmed in small groups during exercises.

The MRI course is normally taken in the second semester by students enrolled in the imaging study line of the Medicine and Technology graduate program. It is a 5 point course first given spring 2010. In 2011 it had 20 participants. These were both formally and in practice required to have knowledge corresponding to the last course in the spiral program (31545), i.e. familiarity with basic MRI concepts and the corresponding math at a superficial level.

III THE SOFTWARE AND STUDY AIMS

Three-dimensional movies are appropriate for illustrating MR vector dynamics, but only a limited range of these are available. The typical solution employed by educators is hand waving, since arm motions can be used to illustrate vector dynamics to a limited extent. The movement of many vectors must often be visualized simultaneously to explain MRI techniques, however, and the number of arms and other physiological constraints are limiting factors. Many students find such demonstrations confusing, and those who do not grasp the meaning during lectures, are left in a bad position.

For this reason, educational software was developed over the last decade. It can be used directly from the software homepage http://www.drcmr.dk/bloch. The software is since 2010 released in a version that executes directly in almost any web browser. This opens for student exercises which may significantly improve the understanding of MRI concepts. The software is introduced and demonstrated in a series of YouTube videos available via the software homepage. The videos show the software as it may be used in lectures, and they are aimed at new users already familiar with MRI. Conclusions based on the use of this software will likely apply to other educational spin simulation tools also, e.g. SpinPlayer (Benoit-Cattin, 2005) or those by P.G. Björklund (Björklund, 2011).

The Bloch Simulator has been used for years during lectures, but little is known about how it is perceived by students, or whether the new possibility of using it independently in a browser, is used by them. An aim of the current study was to explore this and the benefit. Specifically, it is tested to what extent the software may improve understanding of interactions between radio-frequency oscillating magnetic fields (RF) and nuclear magnetism. It was hypothesized that the lecturer's use of educational software during lectures, and the student's use between lectures, may improve understanding considerably.

IV STUDY DESIGN

The students of the course 31547 on medical MRI were subject to a study approximately half way through the 13 week semester, spring 2011. The test period extended over 4 weeks with the following parts:

- Week 1: Lecture given by students where the topic was introduced, but not covered in any depth.
- Week 2: Traditional lecture with in-depth coverage of the subject.
- Week 3: Lecture with questionnaire followed by exercise.
- Week 4: Repeated questionnaire with some questions changed/added.

These parts are described in detail below.

Introductory lectures

The topic was initially introduced briefly in a 20-minute lecture given by 2 students as done for most new subjects covered in the course. It was subsequently covered in more detail in a fairly traditional lecture

including frequent bidirectional questions and answers, which is typical for the course. On earlier occasions, the simulator had been used for demonstrating concepts of magnetic resonance, but that was not the case when this particular subject was covered initially.
After this lecture the students would optimally have some feel for the subject, but due to the extent and difficulty of the subject, they were not expected to have a thorough understanding. MR techniques rely on quite a few foreign concepts and corresponding unfamiliar terminology that typically needs to be mentioned and used in different contexts before they are remembered and understood.

Pre-exercise test and exercise

The lecture following a week later was initiated with a brief introduction to the study, and the subject of this (whether the MR simulator software improves learning). The students were introduced to the questionnaire and were informed that it was anonymous and aimed at improving the course. It was also said to be intentionally difficult (since a large variance in performance was wanted, this was indeed the aim). The questionnaire contained questions about the simulator and its use (see appendix), for example *"How do you estimate your total benefit of demonstrations using the MR-simulator performed at lectures?"* (answered on a 5 point scale). It also contained 4 multiple-choice questions designed to test the understanding of the topic of interest, for example *"Which 2 properties are most important for a slice-selective saturation pulse, i.e. a pulse aimed at suppressing signal from a slice of tissue"*. One additional lengthy question was included as a filler for those students who answered the 4 initial questions rapidly. The questions were prepared in Danish since all students are Danish speaking and since the lectures were given in Danish. Important definitions and nomenclature for the subject matter (RF pulses and excitation profiles) had been written on the blackboard in advance, and were briefly recapped before the pre-exercise test began.

After 15 minutes of quiz-solving in solitude, the students were asked whether they needed more time to complete the first 4 MR questions. Some did and a few more minutes were given. After that, all indicated that they had finished. They were then given empty envelopes and were asked to put their assignment in the envelope, seal it, and write their name on it. It was again stressed that the questionnaire was anonymous, and the students were informed that they would get the correct answers later. In order to avoid telling that the questionnaire should be repeated next week, it was not explained why they should write their names on the envelope. Knowing could bias the result by making the students practice extra. In hindsight, it would have been wise to tell the students, that they themselves would open the envelopes later. This would remove any doubt of anonymity without giving away the plan.

Immediately following the questionnaire, an exercise was conducted in the class. The students were asked to form groups of 2-3 persons that they happened to be sitting close to. They were then asked to consider how particular aspects relevant for the topic could be demonstrated using the simulator. The questions to be answered are given in the appendix, for example *"How can selective and non-selective excitation be illustrated?"* Optimally, the groups should suggest that short&strong, or weak&long RF pulses can be applied interactively in the simulator to demonstrate differences in selectivity. Using a classroom PC with wall projection, this suggestion would immediately be tried out under student guidance, and be discussed in class. The topics of the remaining questions were also within the same general scope as the questionnaire but the questions in this were not addressed directly. The aim was rather to familiarize the students with the simulator and show them that it could be used to explore the topic covered. After having had a few minutes to discuss each question (too little) selected groups were asked to provide their answers, and corresponding demonstrations were carried out. Apparently no groups had clear ideas of all answers but several students revealed at least partial understanding of the subject. This switch between asking questions, discussing them in groups, and following up in class lasted approximately half and hour.

Post-exercise test

The week after, a slightly modified version of the questionnaire was repeated (see appendix) to test the student's satisfaction with the previous week's exercise, whether they had used the simulator independently in the meantime, and whether their understanding had improved.

Questions about the previous week's simulator exercise and about the student's own use of the simulator in the meantime were replacing prior questions about the general benefit of the simulator. The class was initially asked whether anyone had figured out why they should put their answers in a sealed, named envelope – no one had, and apparently they had not given that much thought, which was good. They were told that they would now get the questionnaire again, and they afterwards would be given back the sealed envelope from last week, which they should open so that both answers could be put in a new unnamed envelope to allow for comparison with earlier answers. The students were subsequently given a copy of the questionnaire with the right answers marked.

IV RESULTS

Subjective impression

The practical execution of the quiz and class exercise subjectively went as well as could reasonably be expected. The time was limited by general constraints and took approximately one hour in total which is too long for a lecture. This was not perceived as a big problem, though the exercise was somewhat rushed to avoid keeping the class even longer before the break and the next scheduled subject.

Results of MR questionnaires

The results of the questionnaires are lengthy and in Danish, so they are only summarized here.

19 students answered both MR questionnaires at least partially. One student was only present the first week, and this student's answers were thus discarded unread to respect the confidentiality promise. 16 of the 19 students reported a good or very good benefit from prior use of the simulator during lectures, and all who answered found the benefit at least acceptable. The comments generally focused on the understanding that visualizations of mathematical and physical concepts provide. Some find them difficult to follow, though. 17 of the 19 students had used the simulator themselves via the Internet, although several had only used it briefly. Approximately half used it to improve understanding. Of the 17 that used it, 2 benefited very much, 7 benefited well, 6 benefited acceptably and 2 benefited little. The benefit correlates with the time spent and with how difficult the operation of the software is perceived. Some indicated that it is difficult to reproduce examples from lectures. One student mostly answered the second set of the repeated multiple choice MR questions, maybe because of late appearance in class. Except for that, all students answered most evaluated questions, so the time seemed sufficient. The 4 multiple-choice MR questions had an approximately even distribution of right and wrong answers in the first session. This is much better than random chance, since more wrong than right options were given. One question was answered correctly by almost all students in both sessions. In 24 cases, answers were correct in both repeated sessions, so improvement was not possible. 17 cases of improved answers (of 48 possible) and 10 cases of worse answers were counted, so overall some improvement from session 1 to 2 was observed, although there was still much room for more. In no cases could the improvements be attributed to independent use of the simulator between the two lectures, since no students indicated any such use. 15 of 19 students, however, indicated that the class exercise with elements of group work had been of much benefit, and 4 indicated acceptable benefit. Hence it is reasonable to attribute some of the improvement to the class exercise, though it is also likely that some of the students have improved their skills in other ways. The comments mostly indicated satisfaction with the exercise.

V DISCUSSION

As hoped, the MR questions were sufficiently difficult to ensure significant variability between students. In hindsight, multiple-choice question 3 may have been confusing, since one of the two properties that were sought in the answer could be seen as included in the other. No students raised this potential issue, after they were provided with the right answers.

The improvement in MR understanding between the two tests is difficult to evaluate since it obviously has no simple relation to the improvement in correctness of the answers to questions. A positive correlation is expected, however, and improved results were found. It was clear that the understanding was not perfect at re-test, which should neither be expected at this point in the course (or in any point, really, since the questions were designed to be sufficiently challenging to ensure variability).

It is a weakness of the study design that improvements in the performance between the two repeated questionnaires can not be attributed to the use of the simulator alone. In addition to participating in the simulator exercise, the students may also have read books in the meantime, for example. However, giving the fairly long questionnaire twice on the same day was deemed demotivating. More importantly, an improved result of the second test would be expected based on student's short term memory alone, which is not the focus of the course teaching. Repeating the quiz twice on the same day would also remove the student's chance to go and use the software themselves between lectures. This option was not mentioned to them, but they did know that the software is freely available.

It is an advantage that the two tests were both started in the beginning of subsequent week's lectures so that conditions were as similar as possible. It would have been a problem, if students only participated in one of the tests, but 19 of 20 possible students participated both weeks.

It was the hope that some students would use the simulator independently between the two lectures but none indicated any such use, and the benefit of this can hence not be estimated. Apparently it is not sufficiently stimulating to know that the simulator is relevant for understanding a particular difficult subject, at least not when students are busy with other tasks. It is likely worth handing the exercise to the students a week ahead of time, and ask them to prepare. The fact that none used the simulator between the two lectures simplifies the interpretation of the observed improvement as the benefit can largely (although not solely) be attributed to the class exercise involving group discussions and use of the simulator.

There was no clear correlation between MR abilities and independent use of the simulator, and even if such a correlation had been seen, it would likely be due to general subject interest rather than direct benefit of using the simulator.

There was little variability in the perceived benefits of the simulator in general and of the specific class exercise, which were both generally high. Any correlation involving those would therefore likely be spurious, and was not looked for.

Overall, it was valuable to get confirmation that use of the simulator in the class is indeed found beneficial. Hitherto, it has not been used as much in class and in exercises, as it could, because of the danger of pushing a technology that may not be found useful by the students. It appears that excessive use is not currently an issue, and that more class/group exercises like the one introduced here, may be beneficial. It is important that the students do not feel saturated, however, especially since non-anonymous critique of the simulator would likely be held back, given that the lecturer/examiner is also the author of the software. Though the current test was anonymous, the results may be biased, as the general impression of the lecturer may influence the opinion regarding use of "his" simulator.

Several answers expressed difficulties using the simulator independently. More class/group use of the simulator may alleviate this. Even more so may the recent publication of simulator demonstration videos on YouTube, where not only the spin dynamics themselves are demonstrated, but also how their visualization is achieved using the simulator. The videos are far from exhaustive regarding the possible uses of the simulator, so they need not give answers for exercises away, which may be demotivating. The class exercise used in the present context is not covered by the videos, for example.

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APPENDIX

The questionnaires used for the study are here translated from Danish to English. In the original, additional space was allocated for answers.

Questions regarding use of the Bloch Simulator at DTU courses (questions asked only in week 3):

The questions below do not only concern the use of the simulator on the course “31547 Medical Magnetic Resonance Imaging”. Also think back to other courses like 31540 and 31545 if you have had them,

The questions are answered anonymously. The answers are used in the planning of the course and for a study conducted by the course organizer.

1. How do you estimate your total benefit of demonstrations using the MR-simulator performed **at lectures** (mark the most precise of the answers below).

- No benefit.
- Low benefit.
- Acceptable benefit.
- High benefit.
- Very high benefit.

Short explanation of your answer: ____

2. Have you used the Bloch simulator yourself via the internet? Yes / No (mark answer with a circle)

Why / Why not:____

3. If you have used the MR-simulator yourself, then please mark which of the following options that best describes your total benefit of the use in these situations.

- No benefit.
- Low benefit.
- Acceptable benefit.
- High benefit.
- Very high benefit.

Short explanation of your answer: ____

Questions regarding use of the Bloch Simulator in week 3 (questions asked only in week 4):

What is your estimate of the benefit of last week's demonstrations performed using the Bloch simulator? (Please mark the most precise answer below)

- No benefit.
- Low benefit.
- Acceptable benefit.
- High benefit.
- Very high benefit.

Short explanation of your answer: ____

Have you used the Bloch simulator in the meantime? Yes / No (mark answer with a circle)

Questions regarding the properties of radiowave pulses in connection with MRI (these question were asked in both week 3 and 4):

Question 1
Mark the correct continuation of the following sentence (or mark "don't know"):
A slice-selective excitation pulse must be followed by a refocusing gradient orthogonal to the slice to...

- ...move appropriately in k-space before measuring.
- ...move appropriately in k-space during measuring.
- ...create a phase roll orthogonal to the slice.

- ...remove a phase roll orthogonal to the slice.
- Don’t know.

Question 2
When “short” or “long” RF pulses are mentioned, the length is relative to the dephasing period. Mark the correct continuation of the following sentence (or mark “don't know”):
For an RF pulse to be frequency selective, it must be...

- ...a long pulse with a relatively broad envelope.
- ...a long pulse with a relatively narrow envelope.
- ...a short pulse with a correspondingly narrow envelope.
- ...weak radiowaves independent of duration.
- Don't know.

Question 3
Which *2 properties* are most important for a slice-selective saturation pulse, i.e. a pulse aimed at suppressing signal from a slice of tissue (mark answers or “don't know):

- The distribution of transversal magnetization orthogonal to the slice.
- The distribution of transversal magnetization along the slice.
- The distribution of longitudinal magnetization orthogonal to the slice.
- The distribution of longitudinal magnetization along the slice.
- The mean tip angle orthogonal to the slice.
- The mean tip angle along the slice.
- Don't know.

Question 4
Please mark the correct continuation of the following sentence (or mark “don't know”):
To rotate the nuclei within a slice of tissue by a specific tip angle,...

- ...the RF pulse frequency and the Larmor frequency are adjusted to each other.
- ...the bandwidth of the RF pulse and the gradient strength are adjusted to each other.
- ...the RF pulse duration and amplitude are adjusted to each other.
- ...the RF pulse phase angle and duration are adjusted to each other.
- Don't know.

An additional lengthy technical question (not included here or evaluated) served as a filler for students who completed the other questions rapidly.

Handouts discussed week 3 in groups and in class after the MRI questions above were answered:

In the simulator, the “Gradient” menu selection can be used to visualize a row of nuclei, present in a field with a gradient. It could, for example, be a row of nuclei located between the ears of the patient with a gradient applied from left to right, so the field varies linearly in this direction. The simulator shows the situation in the frame of reference rotating at the Larmor frequency of the middle nuclei that therefore do not precess visibly after excitation.

The radiowave frequency and amplitude can be varied in the simulator, but not the gradient strength or direction. Specific “rectangular” radiowave pulses with varying tip angle and amplitude/duration can also be applied (with varying selectivity, also known as “hardness”). A rectangular RF pulse is a pulse that has constant amplitude as long as it is on.

The following questions refer to the situation with “Gradient” on, as described above. Please consider how visualization can be done using the simulator. Using it is not part of the task.

Question 1: How can selective and non-selective excitation be illustrated?

Question 2: How can the slice profile for a selective rectangular pulse be illustrated?

Question 3: How can the position of the slice and its thickness be varied?

Question 4: How can the slice profile for a saturation pulse be illustrated?

Question 5: How can the slice profile of an inversion pulse be illustrated?