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Computer-Based Tutorial in MR Imaging

Emanuel Kanal[1,3] and Mark W. Perlin[2]

PURPOSE: To test the effectiveness of customized software as a teaching tool to help the novice understand basic physics concepts underlying the creation of MR images via various pulse sequences. **METHODS:** The authors have developed animating graphic and highly interactive electronic MR audiovisual software for the Macintosh computer in the C programming language, and have integrated it into the classroom setting for teaching MR imaging physics concepts such as T1, T2, T2*, proton density, RF excitation, TR, TE, TI, flip angle, static magnetic field strength, gradient magnetic fields, section thickness, number of phase-encoding gradients, number of excitations, field of view, intersection gap, receiver bandwidth, contrast agent(s), etc. The program interactively demonstrates the effects of these variables upon such imaging objectives as voxel dimensions, section quantity, total scanned volume, signal-to-noise ratio, contrast, contrast-to-noise ratios, resolving power, and scan acquisition time. Partial saturation, gradient echo, inversion recovery, and fat-saturation imaging techniques are included. Written posttests on the syllabus covered in our basic MR course were administered to three groups: 43 student professionals (technologist/physicist/radiologist) (control professional group) before, 149 student professionals (exposed professional group) after the addition of the tutorial software into the MR course as an integral part of the teaching process, and a group of 200 pharmaceutical sales staff with little to no prior MR or scientific background (exposed pharmaceutical group). The scores were then evaluated and compared among the groups. One hundred ten students exposed to this software also anonymously rated the software on a 1 to 5 scale (harmful to very helpful, respectively) as to their feeling regarding its role in their MR educational experience and the ease with which they were able to understand the material covered in the basic MR course curriculum. **RESULTS:** Mean test scores were statistically significantly lower in the Control Professional Group (60%, ± 2.59 standard error of the mean (SEM)) than in either the Exposed Pharmaceutical (73% ± 0.75 SEM) or Exposed Professional Groups (77% ± 0.99 SEM). The mean subjective assessment score regarding the software was 4.8 (scale 1 to 5). **CONCLUSION:** This custom-developed interactive MR tutorial software is demonstrated to be effective in assisting even those new to MR imaging in understanding the concepts underlying MR imaging physics in a manner that is felt to be significantly more palatable than lectures, articles, and/or textbooks alone.

Index terms: Education, medical; Magnetic resonance, technology; Computers, in education

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We have produced computer-based animated graphic educational software to assist in the teaching of the basic physics concepts underlying clinical magnetic resonance (MR) imaging. Designed initially as an audiovisual teaching aide, its primary objective is to clarify the intricate interdependence of the multiple scan parameters both upon each other and upon the final image. It also shows their effects on critical and universal MR examination objectives, namely, resolving power, volume of tissue/patient imaged, and scan time. Because the concepts underlying clinical MR imaging tend to be heavily based in mathematics and are both visually and conceptually complex, and because radiologists and technologists tend to be visually oriented, we felt that graphically

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structuring and animating these constructs would be the most useful way to present them. Thus, the program is an ersatz MR imager, and its use is an animated, real-time interaction between the student and the computer (imager), with the effects of any variable modification graphically displayed in real time. In effect, then, rather than trying to teach "the right way" to perform an MR examination, the software graphically demonstrates the effects of a parameter change without requiring that the examination (read: experiment) be performed on a patient.

Materials and Methods

Implemented on a Macintosh Computer (Apple Computer, Cupertino, CA), the software is divided into individual "chapters," each emphasizing unique aspects of the underlying physics and related clinical concepts. The software requires the Macintosh operating system, version 6.0.7 or later, is fully MultiFinder and System 7 compatible, and is 32-bit "clean." It will run on any of the Macintosh II family of computers with a 68020, 68030, or 68040 central processing unit (CPU). The software requires 3.5 megabytes of random access memory (RAM), a 68881 or 68882 math co-processor (unless a 68040 CPU is present, which already incorporates the functionality of the math co-processor), and a color monitor with system/monitor capability set to display at least 256 colors simultaneously. No special peripheral hardware or software is required, and all the above computer system configurations are readily available. Each of the chapters is written in Think C, Version 5.0 (Symantec Corporation, Cupertino, CA), using object-oriented programming (OOP). Although others have attempted to develop MR tutorial software on the Macintosh using Hypercard or Supercard environments, our selection of the C (object-oriented) programming language was quite intentional. While significantly more difficult to develop, the speed with which code generated and compiled in this language could be executed would be exceptionally faster in C than in either of the other development platforms, thus permitting the rapid, real-time recalculations and displays of complex waveforms, scanned image appearance, and other such graphic outputs within the programs. The total custom-written source code for all chapters combined is presently well in excess of 12 megabytes. Once compiled as free-standing, stand-alone applications, however, even the largest single chapter and all accompanying files, when compressed, fit comfortably onto a single high-density 1.4 megabyte 3.5 inch floppy diskette.

System Design

The main goal of this software is the accurate real-time display of the effects of changing any of the MR scan parameter options. The system's present configuration allows for the manipulation and real-time integration, recalculation, and animated display of virtually all pertinent variables. For the chapters that discuss the creation of an image involving stationary tissue, user modifiable variables are listed in Table 1.

Since most current imaging systems have 256 frequency encoding steps, the software assumes this number for all simulations; it is not yet a variable. The window and level of the displayed MR slice or phantom can be entirely defined manually by the user or can be set by either of two automated algorithms. The concept of voxel volume and its relationship to pixel intensity is introduced. The software includes a tissue library system that enables the user to select, create, edit, and delete any tissue and its associated T1, T2, T2*, and relative proton density values. Multiple libraries can be created and used simultaneously, each containing an almost unlimited number of tissues, which the user can define and redefine.

The tissue library function also stores the tissue response to the administration of any real or theoretical MR contrast agent. For example, we might want to explore images created using a theoretical contrast agent that halves T2* but has no significant effect upon T1. The user can observe and make side-by-side comparisons of images from various field strengths, with and with-

TABLE 1: User modifiable variables

Static magnetic field strength (B_0)
Pulse sequence type
Number/type of tissues displayed
Tissue T1
Tissue T2
Tissue T2*
Tissue proton spin density
TR
TE
TI
Presence or absence of any number of real or theoretical MR contrast agents
Excitation flip angle
Slice thickness
Interslice gap
Number of acquired slices
Number of phase encoding steps performed
Field of view
RF transmitter bandwidth
Receiver bandwidth
Background random noise
Number of excitations
Scan acquisition time
Voxel volume
Imaged volume
Resolving power
Signal-to-noise ratio
Contrast-to-noise ratio

out a contrast agent. Finally, tissues can be easily transferred across libraries, allowing for easy and rapid distribution and dissemination.

In the chapter discussing the generation of an echo, or signal, the mechanisms by which spin and gradient echoes are obtained are explained and graphically demonstrated. Some of the differences between gradient and spin echoes are also highlighted and displayed. In this chapter, the variables that can be manipulated include gradient strength, power/time of the 180/90° pulse, TE, TR, flip angle, and tissue types and their associated relative proton density, T1, T2, and T2* values.

The chapter on slice selection demonstrates slice selection and excitation. As always, all pertinent variables can be modified by the student, including, but not limited to, gradient amplitude, slice thickness, slice location, gradient symmetry, static magnetic field strength, and transmitted RF frequencies and bandwidth.

In the chapter on flow, factors such as flow rate, magnetic properties of the fluid itself (T1, T2, T2*, proton densities, and contrast agent response), presence or absence of contrast agents, flow direction, viscosity, number of slices to be excited, thickness and location of the excited slice within a multislice study, interslice gap, excitation order, TR, TE, and RF excitatory flip angle are among the variables which can be modified.

Imaging sequences available throughout the combined chapters include partial saturation spin echo, gradient recalled echo (both spoiled as well as nonspoiled residual transverse magnetization), fat saturation, and inversion recovery techniques, including short TI inversion recovery (STIR). This has proven to be valuable since it visually shows the student how radiated energy gives rise to the image. Finally, we illustrate the difference between choosing to "spoil" or to preserve residual transverse magnetization in gradient recalled echo imaging sequences.

One of the high points of the program is its graphic display of the proton moment vector in both the proton's spinning reference frame and the inertial frame of the magnet (Figs. 1 and 2). These two frames are displayed side by side for easy comparison, allowing the student to look back and forth between the two to understand the complex motions occurring. This method has been more fruitful, and much less instructor intensive, than any lecture or other aid was have tried to date.

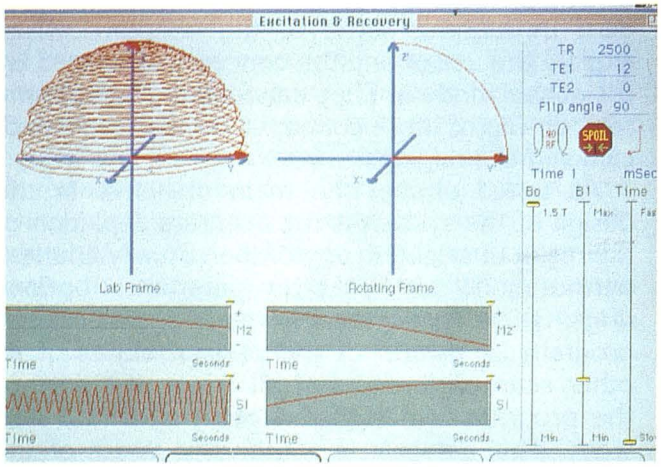
Context-sensitive Help screens assist the student throughout some of the chapters. They explain the use of and the concepts illustrated by the active window. They can further illustrate the relationship of these concepts to other aspects of clinical MR imaging.

As noted above, the main objective in the design of the system is the accurate depiction of the result of selecting any of the virtually limitless permutations of MR scan parameter options (Figs. 3–7). To ensure that each section of the program is "aware" of the present status of all other scan parameters at all times, the core of the program is designed around a central network. This network is continually aware of the status and value of every scan parameter. The network calculates the effects of each parameter selection and then graphically depicts those results, in various ways, simultaneously. The central network processes all input and output functions. The network "bottleneck" ensures coordinated and simultaneous screen updates for all parameters and graphic displays each time the student manipulates a variable. In this sense, the network corresponds to the physical reality of matter; the program does not allow for "cheating."

Experience to Date

We incorporated the tutorial software into the lecture series of the Magnetic Resonance Education Programs of our Division of Magnetic Resonance. This quarterly MR course consists of a fixed curriculum of lectures on basic MR imaging physics. Beginning in April 1990, the course also included a heavy emphasis on using this MR tutorial software in the curriculum as an audiovisual teaching aid.

The total professional experience and knowledge level of the students for each course is quite varied. We teach technologists, nurses, physicians, radiologists, and physicists, as well as lay people from pharmaceutical and MR manufacturing companies. At the conclusion of the basic curriculum of each course, a student must pass a standardized written examination covering the basic curriculum in order to receive a diploma. The examination questions are chosen from the same pool of 100 questions (randomized order and order of choices in the answers), of which half are true/false and half are multiple choice. In the latter type, any possible combination of selections, one or more, may be true. In such a question, if any combination of answers other



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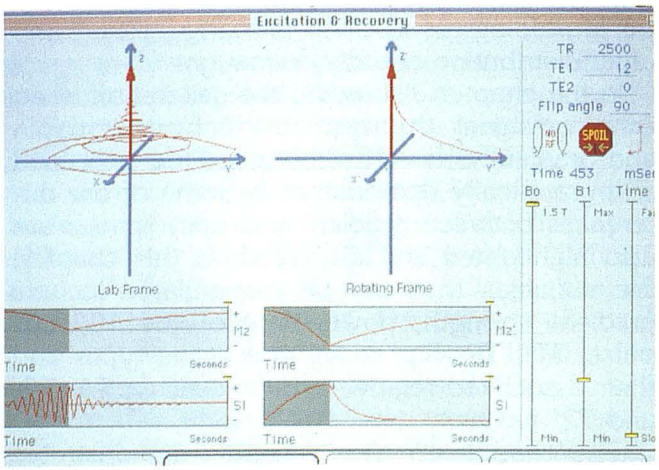

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Fig. 1. This is a screen from chapter 1 where the trace mode is enabled to allow the student to follow more easily the three-dimensional animation occurring on the screen. Depicted is RF excitation, with the laboratory, or stationary, frame of reference displayed on the left and the rotating frame on the right. The magnetization vector of a single tissue is displayed as a *red arrow*, now after a 90° RF excitation pulse pointing to the right. The graphs at the bottom of the screen show vertical (Mz) and horizontal (My) magnetization components for the tissue(s) over time, with the upper graph plotting Mz and the lower plotting My. Similarly, the graphs on the lower right of the screen are the same as those on the lower left of the screen, but showing the same data from the rotating frame of reference.

Fig. 2. After the 90° pulse from Figure 1 was turned off, the magnetization of the tissue was allowed to recover vertically and decay horizontally. The path taken by the tissue net magnetization vector during this process (based on the T1 and T2 values of the tissue) is depicted in the display in the upper half of the screen and plotted in the graphs in the lower half of the screen for the laboratory and rotating frames of reference.

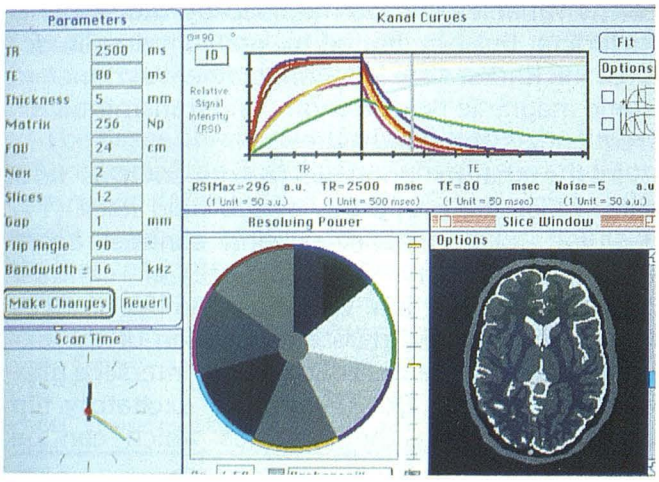

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Fig. 3. This is a typical screen appearance from chapter 4, where the parameter list is on the left, the graphically manipulable tissue relaxation and recovery curves on the upper right, scan time display on the lower left, and phantom and head slice images are on the lower middle and right of the screen, respectively.

than the correct one is chosen, the entire question is marked wrong. Sample questions appear in Table 2; each is a sample of a point covered in the first week of the course and graphically illustrated, and indeed explained, by the tutorial software.

We compared the test results of students taking the three courses held immediately before the introduction of the tutorial software as part of the course with the test scores of subsequent students who used the software extensively. The curriculum and lecturers were otherwise unchanged.

We also taught the basic MR course in mid-1991 to 200 sales representatives of a pharmaceutical firm in the same 5-day time frame, with extensive incorporation of the interactive graphics of the software into the training program. The vast majority of these individuals had had little or no exposure to MR, clinical or scientific, before attending this course. Few had advanced technical or scientific background. They took the same 50 question examination as did the professional groups (exposed and unexposed).

In addition to comparing the test grades, we also assessed subjective impressions of the usefulness of this software. Students were asked to complete (anonymously) questionnaires regarding their feelings about the use of this software as a teaching tool. We asked them whether the custom-designed MR software tutorial ". . . assisted you in your understanding of the information being taught as the prospectively stated objectives of the lecture?" This question was

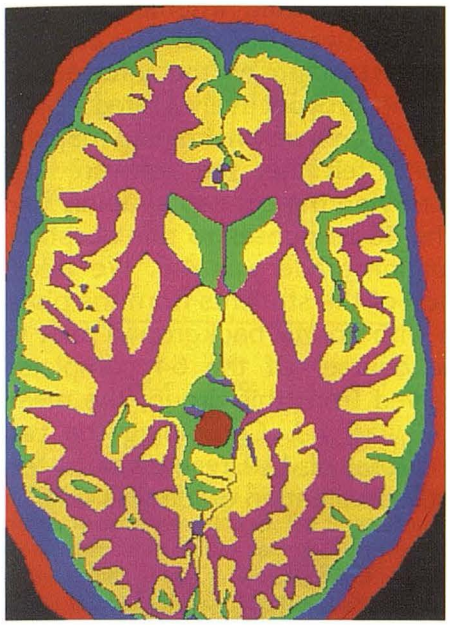

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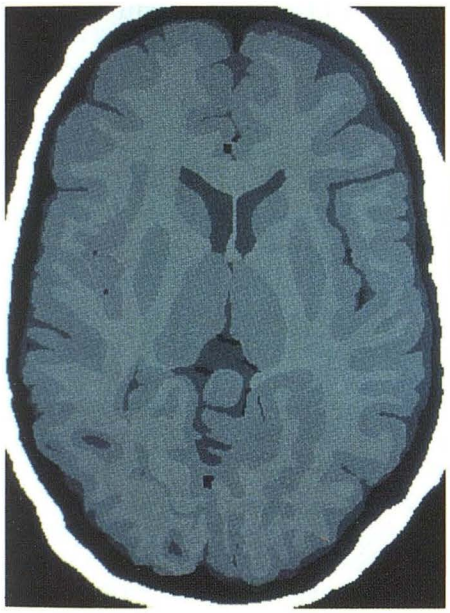
Fig. 4. The user can edit the tissues and their sizes, locations, and orientations within the displayed slice(s). This is a full screen shot of a slice where a midline tumor, marked in red posteromedial to the thalami, was added to the patient's anatomy depicted in this slice. Each tissue is color coded in this mode to allow the user to easily identify and outline the tissues in the image.

Fig. 5. In the same image as in Figure 4, the user has now left the editing mode and returned to the display mode. A short TR (500 msec) and TE (12 msec) partial saturation spin-echo study was selected at a field strength of 1.5T. The imaging matrix selected was 256 × 256 with a 20-cm field of view, 2 excitations, a 5-mm thick slice, and a receiver bandwidth of ±16 kHz.

Fig. 6. Same as Figure 5 except the TR was changed to 2500 msec and the TE to 80 msec.

Fig. 7. This is the same as Figure 5 except that the user has now elected to administer a gadolinium chelate. (The automatic window and level mode for image display is also activated.) Notice the contrast enhancement in the tumor that was otherwise isointense to gray matter on the two unenhanced images displayed in Figures 5 and 6. Also incidentally noted to be enhancing are several vascular structures evident in the slice.



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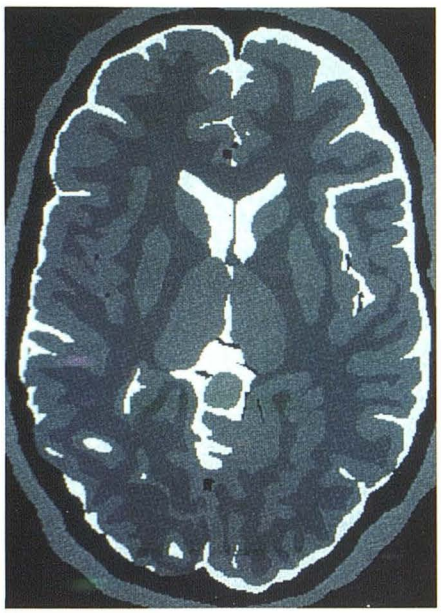

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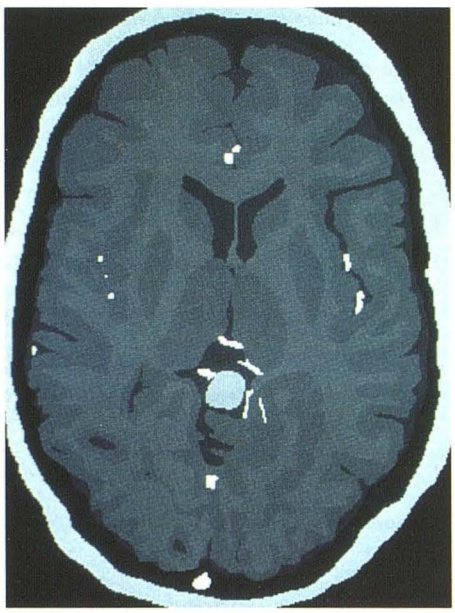

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answered on a 1 to 5 scale, with 1 representing a hindrance to their education, 3 representing no significant impact, and 5 representing a very beneficial effect.

Results

Figure 8 shows the test scores. Of those taking the course in the unexposed professional group, 68% were technologists (the rest were predominantly physicians and physicists); of the exposed professional group, 44% were technologists. The mean test grade for the exposed professional group (77.0 ± 0.99 standard error of the mean (SEM) for 149 students) was higher than that of the unexposed professional group (60.4 ± 2.59 SEM, for 43 students). (We found it interesting that with the use of the tutorial software we could actually *decrease* the course time from 7 to 5 business days (by rearranging the scheduling of some of our clinical read-out sessions to later in our multiweek course) without a decrease in scores.)

The mean test score for the pharmaceutical group (73.0 ± 0.75 SEM, 200 students) was slightly lower than that of the exposed profes-

TABLE 2: Sample examination questions

1. After an RF pulse, the ultimate height that the vertical component of the tissue's magnetization is trying to attain (ie, the height that the recovery curve in the graph is attempting to reach) is determined by the:
   a) relative proton density of that tissue.
   b) strength of the external magnetic field.
   c) T1 of that tissue.
   d) a and b.
   e) all of the above.

2. In multislice imaging, the number of slices obtainable in a given series is dependent upon the selected:
   a) TR.
   b) TE.
   c) receiver bandwidth.
   d) shortest tissue T1 being imaged.
   e) shortest tissue T2 being imaged.

3. The rate of vertical magnetization recovery:
   a) is described by the T1 of that tissue.
   b) is dependent upon the strength of the magnetic field to which the tissue is exposed.
   c) decreases with increasing field strength.
   d) is also known as spin-spin relaxation.

4. The contrast to noise ratio of a specific tissue pair may be manipulated by the:
   a) TR.
   b) TE.
   c) number of phase-encoding steps.
   d) field of view.
   e) NEX.
   f) administration of exogenous contrast agents.
   g) slice thickness.
   h) type and positioning of the specific receiver coil used.

5. The ability to detect and differentiate adjacent structures is *always*:
   a) dependent upon the contrast-to-noise between the tissues being examined.
   b) increased with decreasing field of view.
   c) increased with smaller voxels as compared to larger ones.
   d) improved with the administration of contrast agents.

sional group. Indeed, the pharmaceutical sales population, with no prior MR knowledge and limited technical background, performed better as a whole than did the group of professionals with no exposure to the tutorial software.

When compared using an analysis of variance and Tukey HSD multiple comparison tests, the scores for the unexposed professional group proved to be statistically significantly lower than those of the exposed professional group ($P < .001$) or the pharmaceutical group ($P < .001$). Interestingly, the difference between the scores achieved by the exposed professional group and those of the pharmaceutical group also demonstrated statistical significance ($P < .01$).

When students were asked whether the custom-designed MR software tutorial ". . . assisted you in your understanding of the information being taught as the prospectively stated objectives of the lecture?", an overwhelmining majority of the respondents felt that the software was quite good at clarifying the concepts rapidly and efficiently. Of the 46 responses to this question, the mean evaluation grade was 4.9. We asked the same question of the students from the pharmaceutical firm with no MR background prior to their taking the course. Of the 64 completed evaluations received from this group, the mean evaluation grade was 4.7. Combining the two groups, out of a total of 110 responses to this question, the mean evaluation grade was 4.76.

Discussion

MR has progressed over the past decade, with significant advances in both pulse sequence and hardware design occurring on at least an annual basis. Soon after its introduction around 1983–1984, a working knowledge of the interactions among TR, TE, T1, T2, and proton spin density values was, for the most part, sufficient to understand most of the physical interactions underlying this tool. Understanding the interactions among field of view, slice thickness, number of phase-encoding steps performed (Np), number of frequency-encoding samples measured per echo, interslice gap, and the number of excitations (NEX) enabled the diagnostic radiologist to comprehend the interactions that determine image quality and appearance.

The past few years have seen major advances in the diagnostic capabilities of MR. Such advances have included:

1. the advent and routine clinical application of modified flip angle gradient echo imaging techniques;
2. the availability of markedly shortened TE and TR times as compared to those first applied years ago;
3. the appearance of contrast agents of various types and purposes;
4. faster acquisition spin-echo techniques, including:
   a. fractional echo imaging;
   b. partial excitation imaging;
   c. the imminent introduction of echo planar imaging techniques and its variants, such as fast spin-echo imaging;

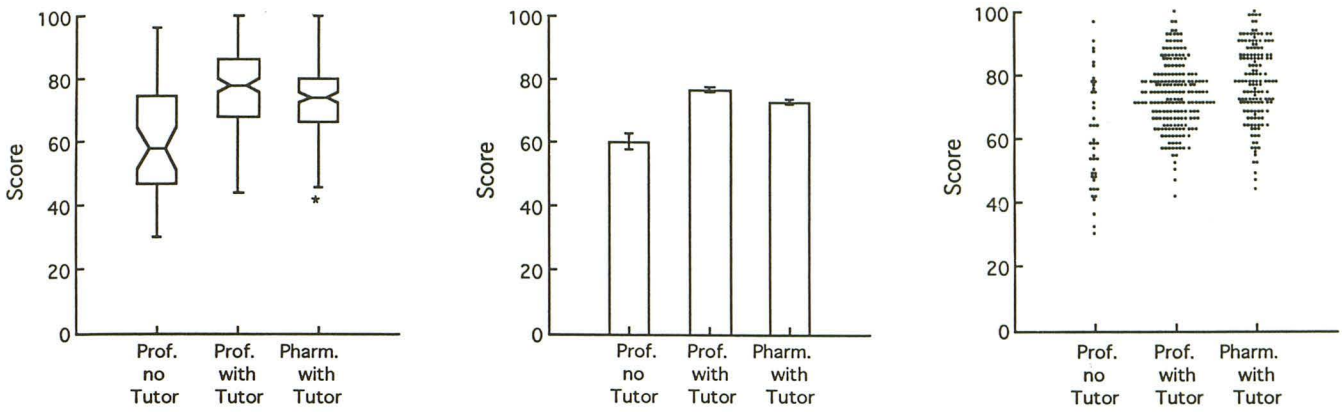

Fig. 8. Plot *A* is a Box Whisker Plot (first described by Tukey) of the data for the three groups. The horizontal bar in the middle of each group represents the median test score. The upper and lower horizontal bars for each group traverse the H spread (ie, the middle 50% range of the scores for each group). The waist in each plot traverses the 95% confidence interval for the median values; the fact that these do not overlap for the three groups attests to the statistically significant difference between their median values. The upper- and lowermost extent of each plot represents the minimum and the maximum of the data (the *asterisk* represents a statistical outlier for the results in that group). Plot *B* shows the mean test scores for the three groups compared, the professional group not exposed to the MR tutorial software, the professional group exposed to the tutorial software, and the pharmaceutical group exposed to the software. The error bars represent the standard error of the mean. (The standard error of the mean represents the reliability of the mean value for each group.) Plot *C* represents the actual scores for each individual in the study.

5. elucidation of much of the physics associated with hemorrhages of various ages;
6. narrow bandwidth imaging techniques;
7. motion suppression techniques;
8. fat-signal cancellation techniques;
9. the investigation and clarification of much of the physics of flow-related phenomena in MR imaging studies, leading to the introduction of MR angiography as part of the daily routine of clinical MR radiologists; and
10. advances in both RF and gradient coil design.

What was considered an adequate knowledge of MR physics in 1984 is therefore considered elementary today, and what was then considered advanced or esoteric is now thought basic or intermediate at best. Physicians and MR technologists who are new to the modality in 1992 therefore are at a considerable disadvantage to those who began years ago, since they have to master a much larger body of knowledge to understand the processes and concepts behind even basic, "routine" clinical imaging sequences used today.

Many have found the computer to be a powerful tool in medical education and diagnostics (1–4). We have developed our software in an attempt to address the MR growth issues noted above and to ease the transition from neophyte to professional. The fact that the mean test score of the tutorial exposed pharmaceutical sales group was almost as high as that of the tutorial-exposed professional group provides evidence of the software's ability to assist teaching the physical phenomena underlying MR, even to those with little or no scientific background. Indeed, the fact that the pharmaceutical sales population with no prior MR knowledge and limited technical background outperformed, as a group, (mean score of 73.0 for this group of 200 students) the group of professionals with no exposure to the tutorial software (mean score of 60.4 for this group of 43 students) provides further evidence that reducing these concepts to interactively animating pictures increases the ease and success with which this knowledge can be assimilated even by those with relatively meager scientific and technical backgrounds.

Limitations

It is exceedingly difficult to control for all possible variables in age, sex, educational background, and even lecturing styles over time between the groups whose standardized MR test performances are being analyzed. Teaching methods may have changed over time, even though the same lecturers have taught the course since the mid-1980s. It is also possible that the individuals making up the later courses were more knowledgeable and/or intelligent than those in the earlier courses, the latter of which had no exposure to the customized MR tutorial software. Nevertheless, although it cannot be called "proof,"

the performance of the 200 students with little to no technical or scientific background does provide evidence of the usefulness of this teaching tool, even to nonmedical personnel. Subjective assessments and statements overwhelmingly attest to the success with which this approach eases the assimilation of the sizable MR knowledge base in a very short time.

Future Growth

We are currently writing software to incorporate several other MR industry advances into the main program. The first such development is the impact of using three-dimensional Fourier transform algorithms. This program simulates exciting a volume of tissue rather than a stack of slices, and will show how thinner slices (and more of them) can be obtained, why interslice gaps are eliminated, why signal-to-noise ratio is improved, how multiformatting capabilities derive from the technique, and why this technique takes longer than similar two-dimensional Fourier transform sequences. Secondly, we are coding for chemical shift effects, and the interaction between receiver bandwidth and the strength and direction of the frequency-encoding gradient upon the appearance of this effect in the image. We have already begun the comprehensive integration of sound files and auditory capabilities throughout the software. This addition may prove most useful in the integrated help system as it permits the user to concentrate on the screen as the program's help files "lecture" audibly to the student. This arrangement has several benefits. It permits the student to concentrate on what is being graphically illustrated, instead of forcing the student to concentrate on reading one part of the screen while, at the same time, animating a point elsewhere on the screen. Furthermore, audible help files permit the screen to be more appropriately used for graphic animation instead of for simple help text, which may not be as effective or efficient at "illustrating" the point being made. Animation sounds have already been incorporated into many other areas of the software to add to the accuracy of the sounds for scanning modes, etc. We have also found that playing a sound such as a digitized camera's shutter release while the screen flashes, as if a flash photograph were just taken, helps to reinforce concepts such as signal sampling, which actually occurs only at very specific times (TE), as selected by the MR operator/student.

We are already in the process of using this software as the graphical front end of an MR expert system, as an in silico simulator. This expert system provides actual recommendations on *how* to scan (ie, it provides the values of each possible MR imaging parameter), given diagnostic considerations and user-controlled constraints (eg, scan time limitations). The system predicts how to optimize pulse sequences for various imaging tasks and constraints. Preliminary tests on phantoms, and more recently on humans, have been most promising.

Conclusions

We have developed customized, computer-based, interactive MR imaging educational software targeted at giving technologists/radiologists a clearer and more comprehensive understanding of the concepts underlying the formation of a good diagnostic clinical image. The intuitive, interactive graphic interface and the rapid, real-time update of visual material on the screen seem ideally suited to the educational process, especially for radiologists and radiologic technologists who are already most comfortable dealing with images. Our preliminary studies on over 300 of our own students to date, as well as evaluations by beta evaluation sites using this software in their own educational pursuits, strongly suggest that this software teaching method provides a considerable educational benefit over that previously possible with lecturers, videotapes, and/or texts alone.

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