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A simulator for teaching MR image contrast behavior

Geir Torheim,[1] Peter A. Rinck,[1*] Richard A. Jones,[2] and Jørn Kvaerness[2]

[1]*Univesité de Mons-Hainaut, Mons, Belgium and* [2]*MR-Center, N-7006 Trondheim, Norway*

A computer program to create magnetic resonance images simulating the main features of a magnetic resonance imaging (MR) machine was developed on a personal computer. The simulated MR images are calculated using the relevant equations describing a chosen pulse sequence on the basis of proton density, T_1 and T_2 images acquired from whole-body MR equipment. The imaging parameters (i.e., TR, TE, TI, etc.) are provided by the user. This program produces highly realistic simulated images and includes features such as choice of echo time, inversion time, repetition time and flip angle, as well as standard features of image display programs such as setting of window level/width, zooming and region of interest definition. A novel additional feature is the ability to define artificial pathologies in user-defined areas by specifying changes in the relaxation times and proton density. The simulator has been developed for teaching and training purposes. A prototype version has been used for teaching MRI with extremely positive reactions from students.

Keywords: MRI, continuing education, training, computer simulation.

INTRODUCTION

The mechanisms which influence and change image contrast in magnetic resonance imaging (MRI) are quite complex [1]. Understanding the relationship among image contrast, pulse sequences and sequence parameters is difficult and often requires much intuition and imagination. Therefore, there is a need for teaching tools beyond textbooks and slide presentations.

The best teacher is an MR machine itself. However, learning by experience is time-consuming, expensive and, in cases with human pathology, impossible. Thus, the next best tool is an MRI simulator; a computer program that simulates the images obtained with an MR machine without performing real examinations. This article describes an MRI simulator which runs on inexpensive and easily available computers of the PC family.

DESIGN PRINCIPLES

Cognitive theories and experiments suggest that students learn better and faster when they have the opportunity of actively participating in the process. In addition, it has been demonstrated that feedback is essential in all teaching situations [2–4]. The reasons behind these principles are beyond the scope of this article but are basically related to learning and cognitive processes [5]. A simulator represents an optimal tool incorporating both principles. First, the student is required to operate the simulator and is thus an active participant. Second, the results of the operations are displayed on the screen and provide immediate feedback to the student.

Thus, the MR Image simulator has been designed according to the following guidelines [2]:

- The user should be in control.
- The response to the user's actions must be as fast as possible.
- It should be possible to reverse all actions with as little effort as possible.
- The program should not allow the user to make serious mistakes.
- The same actions must always lead to the same result.
- The same visual coding used on the screen must always have the same meaning.

Both the preprocessor (described in the next section) and the simulator have been developed using object-oriented methods [6]. The class hierarchies have been designed in a way that makes it easy to

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* *Address for correspondence: Université de Mons-Hainaut, Faculté de Médicine, Laboratoire de RMN, 24, avenue du champ de Mars, B-7000 Mons, Belgium.*
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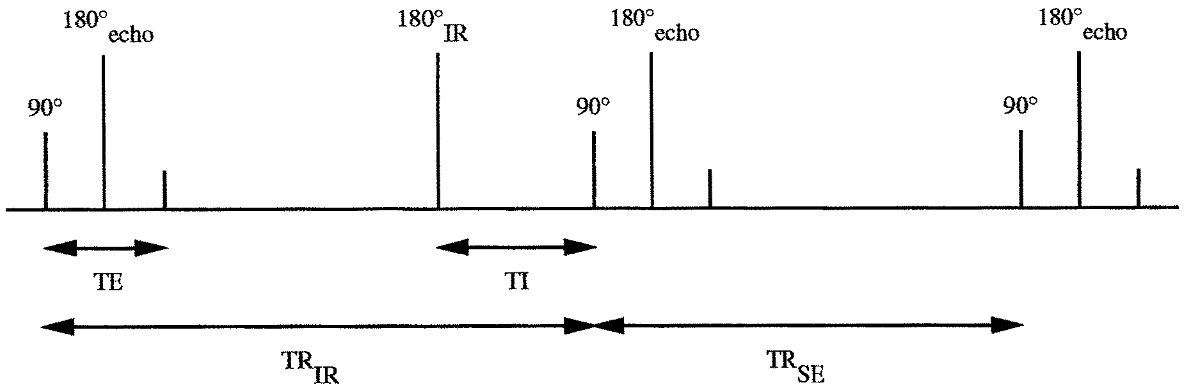


Fig. 1. The mixed-mode sequence currently being used consists of a multiecho spin echo (SE) sequence interleaved with a multiecho inversion recovery (IR) sequence. TE is echo time (for SE), TI is Inversion Time, TR_{IR} is the time between a 90° SE pulse and the closest following 90° IR pulse, TR_{SE} is the time between the 90° pulse after the TI interval and the closest following 90° SE pulse. Typical parameters on the 1.5-T machine for an acquisition from the head were TE 50 ms, TR_{SE} 760 ms, TI 360 ms and TR_{IR} 2220 ms. This gave a total scan time of approximately 20 min.

extend the systems with new functions. In addition, the user-interface part of the system has been separated from the application program, making it easier to move the simulator to another platform (e.g., Macintosh or UNIX).

The simulator has been implemented on a personal computer running Microsoft Windows 3.1 (Microsoft Corp., Redmond, WA, USA). The programming environment was Borland C++3.1 with Applications Frameworks (Borland Corp., Scotts Valley, CA, USA).

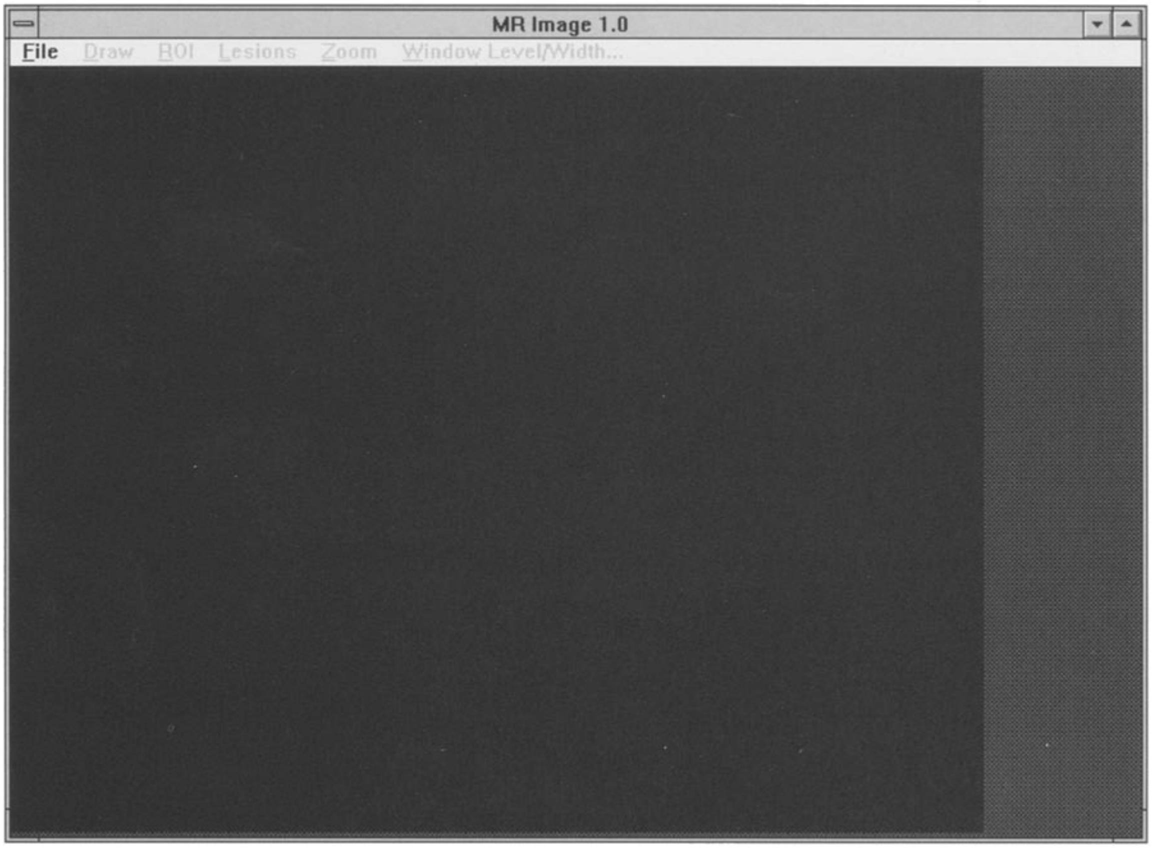


Fig. 2. The simulator at startup. Actions are selected from the menu bar. Only the *File* menu can be selected at this point. All other menus are disabled. See the text for further details.

The Borland Resource Workshop and Borland Object Windows were used to develop the user interface.

METHODS

Data acquisition

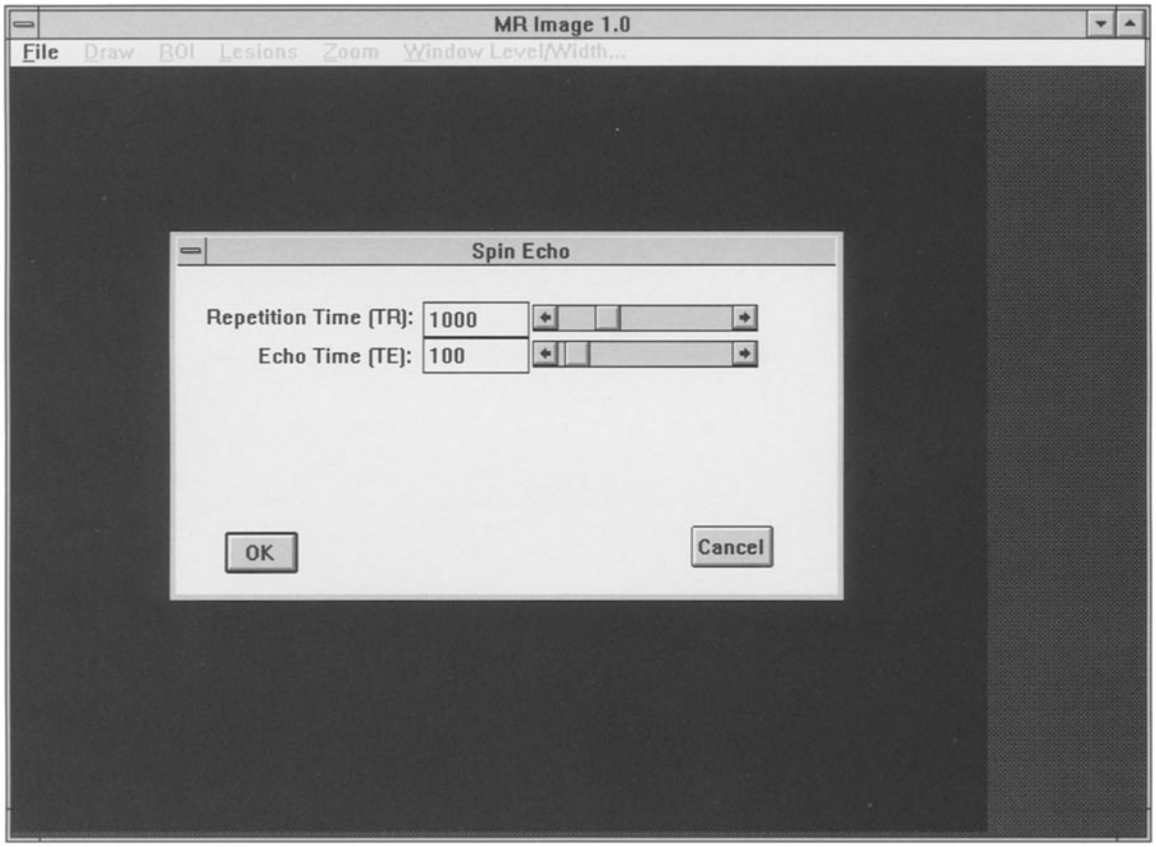
As a basis for all of the calculations performed by the simulator, proton density (ρ), T_1 and T_2 values are required for each pixel in a particular image. In order to achieve this, image data of real examinations were obtained by running a mixed-mode pulse sequence as shown in Fig. 1 [7, 8]. Although not as accurate as multipoint fitting using inversion recovery (IR) and multiple spin-echo (SE) sequences, this method is much less time-consuming and provides reasonably accurate values. This kind of raw data acquisition was performed for the most popular normal anatomical views and for a number of slices through pathologies.

On the basis of these data, ρ, T_1 and T_2 for every picture element in the image were calculated [9]. Data acquisition was performed on two whole-body systems (Philips Gyroscan T5 II 3 at 0.5 T and S15-HQS at 1.5 T). The number of averages was 4, and the image size was 256 × 256.

Data processing

The raw data were transferred from the MR machines to a personal computer and processed using a specially designed preprocessor. The purpose of the preprocessor is to build a database consisting of anatomical views. In most cases, a list of predefined artificial lesions is connected to each anatomical view. The preprocessor performs the following functions:

- The raw data values can be edited interactively.
- Artifical lesions can be defined for each set of raw data (each anatomical view). Each lesion may consist of an arbitrary number of distinct or overlapping regions of any shape and size, allowing simulations of composite lesions. Simulation of injection of contrast agents is possible.
- Compression of the raw data. The purpose of the compression is not to reduce the space occupied



Repetition Time (TR): 1000
Echo Time (TE): 100

Fig. 3. The user has selected the spin-echo sequence and the simulator displays the corresponding dialog box. Upon clicking OK or pressing the ENTER key, the box is closed and a spin-echo image is calculated on the basis of the parameters in the dialog box and displayed.

by the raw data but rather speed up the simulation process. The speed is typically improved by a factor of 5–12, depending on the raw data and the compression rate. A high compression rate will, in general, give faster simulations at the cost of a lower image quality.

The resulting data (including the predefined artificial lesions) were written to a database which is scanned by the simulator every time a specific anatomical view is required.

Image simulation

By using steady-state equations describing inversion recovery, spin echo, different gradient echo and specific RARE sequences, the simulator is able to calculate artificial MR images pixel by pixel based on user specified sequence parameters.

For spin echo, the following equation was used [1]:

$$I = \rho(1 - e^{(T_E - T_R)/T_1})e^{-T_E/T_2}$$

For inversion recovery, the following equation was used [1]:

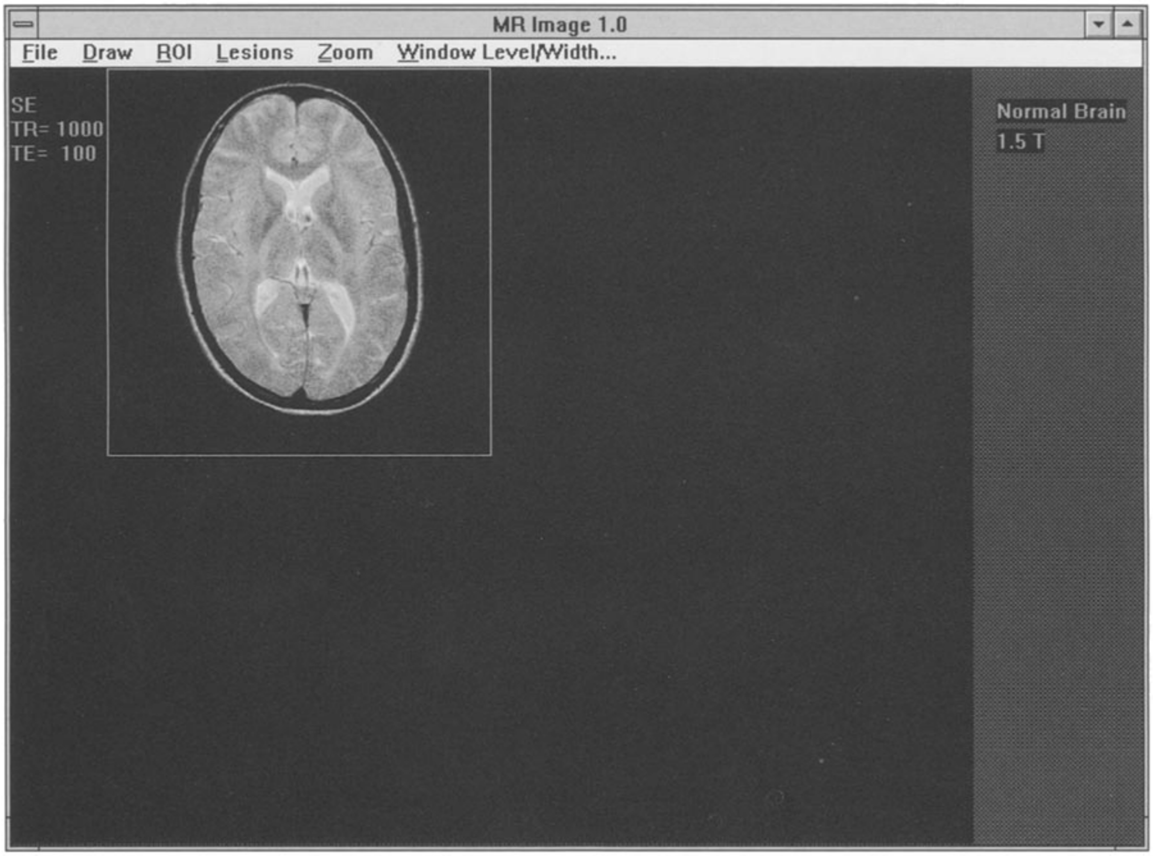
$$I = \rho(1 - 2e^{-T_I/T_1} + e^{-T_R/T_1})$$

The equations for the gradient echo sequences were obtained from Refs. 10 and 11. These equations assume perfect 90° and 180° pulses and a rectangular slice profile. Flow and diffusion effects were neglected. In addition, the inversion recovery calculation assumes a short echo time thus allowing T_2 effects to be neglected.

In general, in the calculations for the gradient echo sequences T_2 was used rather than $T_2{}^*$. This will result in errors at long T_E values or at interfaces between regions of different susceptibilities. Flow effects that are characteristic of gradient echo sequences are not present because the raw images of ρ, T_1 and T_2 are spin-echo images. Similarly, the T_E dependence of the chemical shift is absent for the same reason.

The simulator offers the following functions:

- Setting of Window Level and Window Width.
- Definition of regions of interest (ROIs). ROIs can



SE
TR= 1000
TE= 100

Normal Brain
1.5 T

Fig. 4. The spin-echo image which was defined in Fig. 3. In the upper right corner, a description of the imaging parameters and the field strength are displayed.

be of any shape and size; this function displays minimum, maximum and mean intensity, number of pixels in the ROI, and the average ρ, T_1 and T_2 values for the defined region.

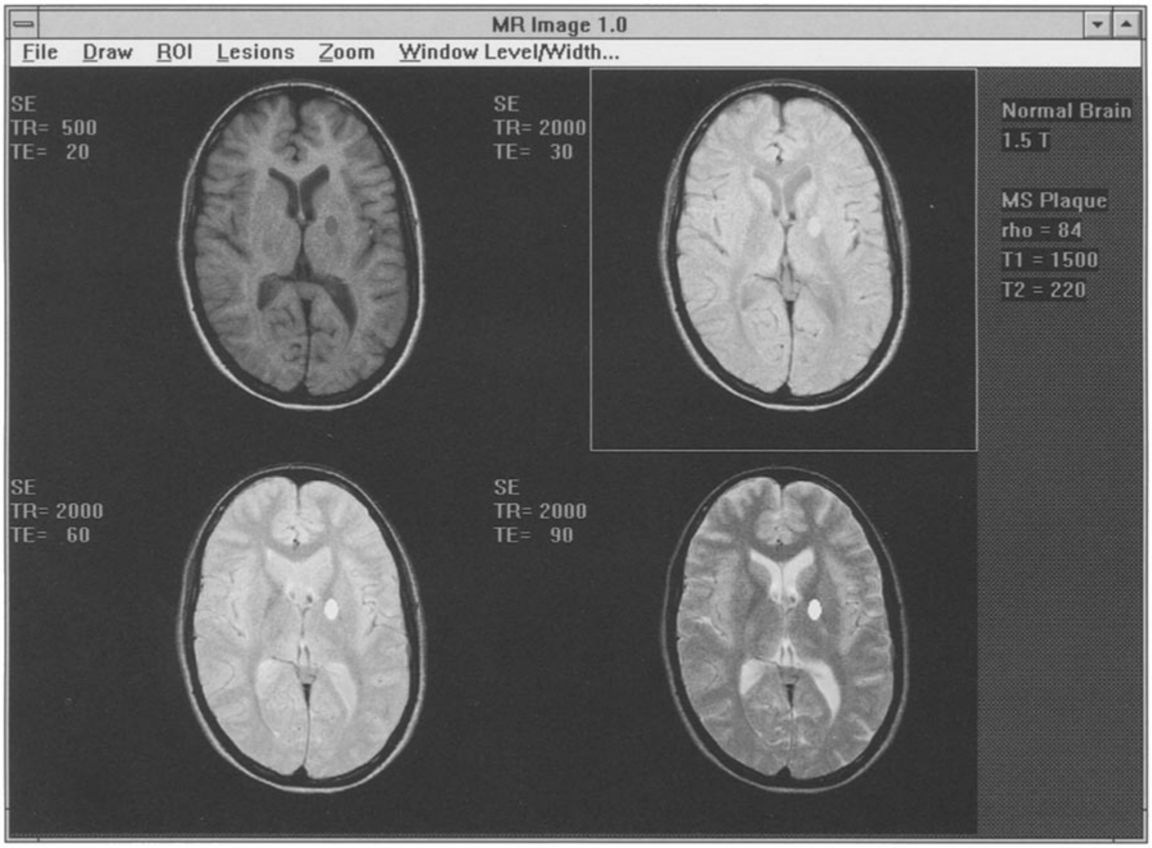
- Zooming.
- Selection of predefined artificial lesions; when the user works with a specific view, the simulator automatically loads the artificial lesions defined for this anatomical view and makes them accessible via a pop-up menu; the predefined lesions cannot be altered by the user.
- Definition of artificial lesions; in addition to selecting predefined lesions, the user can define artificial lesions himself; the properties of already defined (user-defined) lesions can be altered, allowing the simulation the injection of contrast agents, such as Gd compounds.
- Saving/loading of user-defined lesions; the lesions defined by the user can be saved and loaded in a later session with the simulator.

The simulator also allows the user to work with several images simultaneously, making it possible to compare different pulse parameters both qualitatively (i.e., visually) and quantitatively (i.e., by using ROIs). As the program performs simulations based on real image data, this means that it can give realistic simulations of pathologies based on patient raw data. The program is able to calculate and display a simulated image in 2–3 s.

User interface

This section, together with the captions for Figs. 2–7, gives a detailed description of the user interface.

As shown in Fig. 2, the simulator has a standard Windows 3.1 user interface. The actions are issued from the menu bar. The images are displayed on the black area (the drawing area) below the menu bar. The gray area to the right of the drawing area is used for displaying information about the image and the current artificial lesion (if any). When the user starts the program, only the *File* menu can be selected. The other functions need more information and are thus deacti-



SE
TR= 500
TE= 20

SE
TR= 2000
TE= 30

SE
TR= 2000
TE= 60

SE
TR= 2000
TE= 90

Normal Brain
1.5 T

MS Plaque
rho = 84
T1 = 1500
T2 = 220

Fig. 5. Four images are displayed at the same time, allowing the user to compare the effect of different settings. An artificial lesion (acute multiple sclerosis plaque) consisting of one region has been inserted. To the right, the ρ T_1 and T_2 values for this region are displayed. The white frame indicates the active image.

vated (disabled). This prevents the user from performing any illegal actions. The first action taken by a user is to select *File/Open*. The simulator will then present a list of all cases in the database. After selecting a case, the data will be loaded into the simulator, and the *Draw* item is activated. The user can now select a sequence from the *Draw* pull-down menu. After the selection of a sequence, the program responds by displaying the corresponding dialog box. Figure 3 shows the dialog box for the spin-echo sequence. The user can enter the T_R and T_E values by using either the keyboard or by manipulating the scroll bars. When the user has defined a sequence, the image is displayed, and all menu items are activated. As seen in Figs. 3–7 one image is always surrounded by a white frame. The frame indicates the current active image. Operations (ROI definitions, zooming, setting of window level/ width, etc.) are performed on the active image. The user selects the active image by pointing at it and clicking with the left or right mouse button. A maximum of four images can be displayed simultaneously.

An image is displayed in a free space on the drawing area, if possible. When the drawing area has been filled with images, the current active image is substituted by the new image.

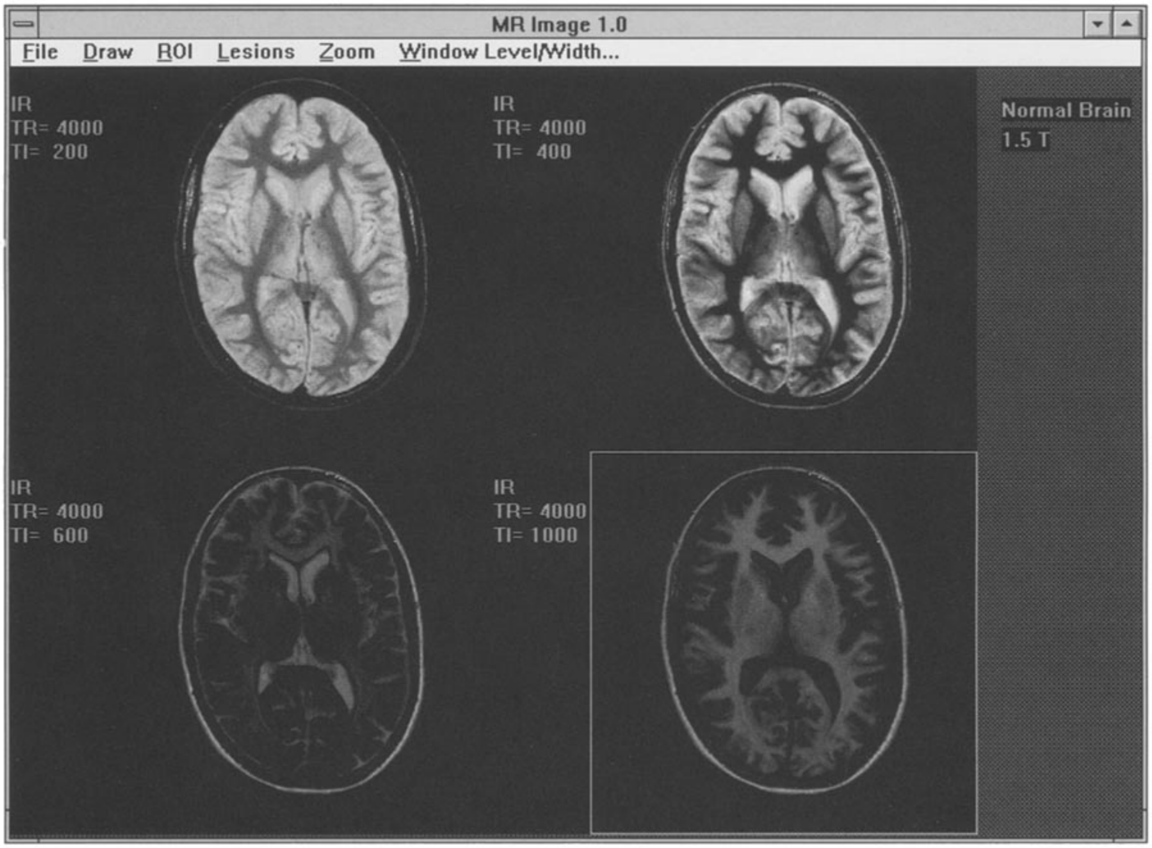
The user defines a ROI or an artificial lesion by manipulating the mouse. How the mouse works depends on the shape selected. The following shapes are available:

- Ellipse
- Rectangle
- Pixel
- Freehand (unrestricted) drawing

In the *ROI* menu, the above shapes are directly accessible. In the *Lesions* menu, they can be selected from the *Shape* submenu. When a lesion consisting of more than one region has been defined, the values for the last defined region are displayed. If the user wants information on one of the other regions, he clicks on it using the left mouse button. A region can be redefined by double-clicking on it. In order to remove a region, the user clicks with the right mouse button while pointing at it. Artificial lesions are calculated and displayed immediately.

Zooming is done by selecting *Zoom In* or *Zoom Out* in the *Zoom* pull-down menu.

When selecting the *Window Level/Width* menu item, a dialog box is displayed, allowing the user to set the window level and window width for the active image.



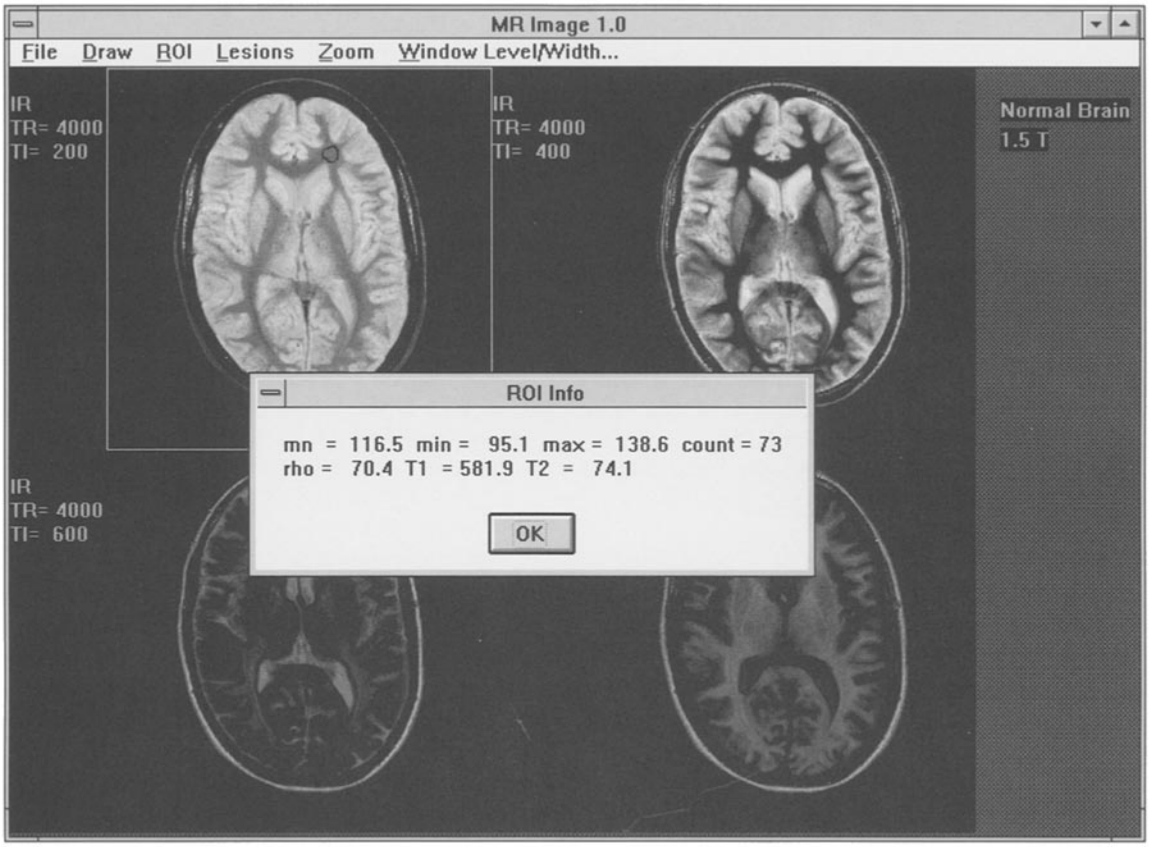
IR
TR= 4000
TI= 200

IR
TR= 4000
TI= 400

IR
TR= 4000
TI= 600

IR
TR= 4000
TI= 1000

Fig. 6. Four inversion recovery images with increasing T_I values. The dramatic change in the contrast is as expected [1].



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mn = 116.5 min =  95.1 max = 138.6 count = 73
rho =  70.4 T1  = 581.9 T2  =  74.1
```

Fig. 7. A ROI has been defined in the upper left image. The ROI was defined by pressing the left mouse button, dragging the mouse, and releasing the button. The simulator displays the ROI information in a dialog box. Four different shapes are available: ellipse, rectangle, pixel and freehand (unrestricted) drawing.

COMPUTER REQUIREMENTS

The following configuration is needed to run the program:

- 386/486 personal computer with hard disk
- Microsoft Windows 3.1
- VGA or SuperVGA screen
- Minimum 4MB memory.

A computer with mathematical coprocessor is recommended due to the large amount of floating-point calculations. A Super VGA screen with 256 colors is recommended; the 256 colors give 64 gray levels compared to the 16 gray levels on a standard VGA screen. However, for most purposes, any VGA screen should suffice. In order to study the finer details in an image, the quality of the screen also becomes important.

EXAMPLES

Because it is an interactive tool, it is impossible in the present article to show how the simulator works. Figures 2–7, however, provide examples of the screen layout and some of the features of the program. All figures show simulated images of a transversal slice through a normal human brain at 1.5 T.

CONCLUSION/DISCUSSION

The teaching and understanding of complex features, such as contrast behavior in magnetic resonance imaging, are greatly facilitated by interactive teaching tools such as personal computers. For the specific task of simulating MR image contrast behavior, we have developed a computer program that simulates part of an MR imager. Contrary to other teaching aids for MRI which use coarse drawings of anatomical pictures, the simulations of this program are based on real MR images and are, therefore, very realistic. An important feature of the program is that it is very simple to use so that the user is not required to spend time learning the tool itself.

The simulator has been used both in classes and in single-student sessions. The comments from the students have been very positive.

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