Graduate Research and Education Program in Magnetic Resonance Imaging

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Abstract

This paper describes the development of a Web site for research and technical education in magnetic resonance imaging (MRI). This site has been developed with funding from the National Science Foundation, and emphasizes MRI theory, medical and biological engineering applications. This Web site is now actively used by UC Davis graduate students. The graduate students find the entire lectures of each MRI course in digitized form, links to information on the NMR facilities on the campus, and help with administrative and financial aspects of their graduate study program.

I. Introduction

One of the main objections raised by engineering and physical science graduate students planning careers in magnetic resonance imaging (MRI) was that the typical MRI textbooks did not give them adequate technical details. Discussions of MR physics, MRI system design, and data collection and image generation were typically “watered-down” for casual reading, and were inadequate for preparation for careers in MRI technical research and development. The courses offered on the Web site to be discussed in this paper provide a rigorous technical education in MRI, and MRI is treated as a scientific discipline to be critically studied. MRI is already being regarded as a sub-discipline and professional focus within Engineering, just as Nuclear Magnetic Resonance (NMR) has reached that stature in Chemistry.

The Web site described in this paper is largely supported by the National Science Foundation Combined Research Curriculum Development (NSF-CRCD) program. The NSF-CRCD Program is a joint initiative of the NSF Directorates in Engineering (ENG) and in Computer & Information Science & Engineering (CISE). The program supports development of curricula in new emerging technologies, and development of new ways of teaching that utilize the new communication technology. MRI is believed to be an important area of need for general US Industry, in particular Food Science, as well as Medicine. This project is a unique collaboration of Radiology, Biomedical Engineering, Food Science and Technology, and Agricultural and Biological Engineering. It brings together both Medical and Engineering Disciplines. Agricultural and Biological Engineering, as well as Food Science, are particular engineering disciplines where MRI will have major impact. The collaboration with Medical departments brought state-of-the art MRI to these non-medical disciplines.

The Web site[1], shown in Figure 1, serves as a repository for technical education in MRI, as an information source on the UC Davis Biomedical Engineering Graduate Program and on

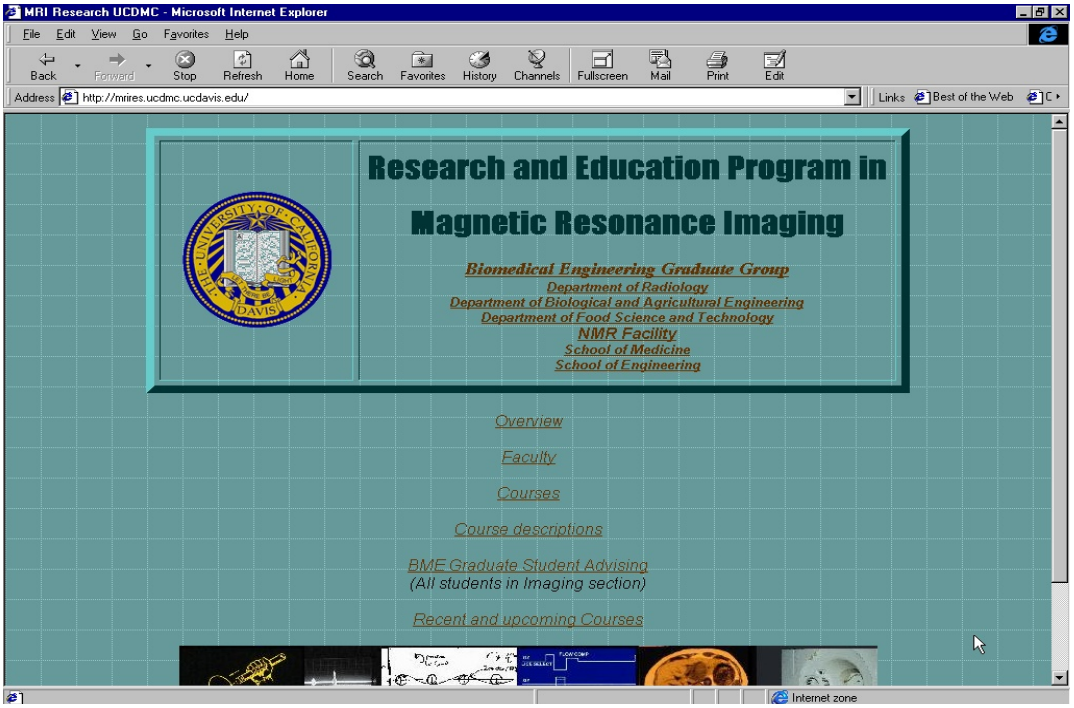

Fig. 1: “Research and Education Program in MRI”, Home page.

individualized Programs of Study, as an information source on the imaging facilities on the campus, and as an information source on other NMR sites.

II. Materials and Methods

Teaching materials consisted of digitized video files of entire MRI lectures, copies of 35 mm slides, student lecture notes, audiotapes of lectures, and for one of classes, the draft a text book on MRI written in *Mathematica*[2].

Microsoft Frontpage editor allowed placement of the frames and pages, and setting of hyperlinks. Front page has many view settings. The normal view setting lets you enter information very like a word processor. In the case of Javascripts or other scripts, it is useful to be able to edit the HTML, and Frontpage allows that (Figure 2). The user can also view other settings, for example, to see how the site will appear in a Browser that doesn’t support frames, or to see what it will look like in Microsoft Explorer.

Digital Video

The pages of the lectures were written on regular paper with the lecturer seated at a podium, with a sVHS video camera above the podium recording the writing, and a video camera in front capturing the lecturer during explanations.

For production of the digital videos, sVHS tapes were digitized at 320 x 240 and 30 frames/sec using an AV Master, Inc. board from FAST Multimedia AG. Adobe Premiere was then used to covert the hardware compressed avi file to a conventional uncompressed avi file, and finally, the RealPlayer Encoder was used to convert the conventional avi file into a extremely small streaming video file which could be viewed over the Web using the RealMedia Player.

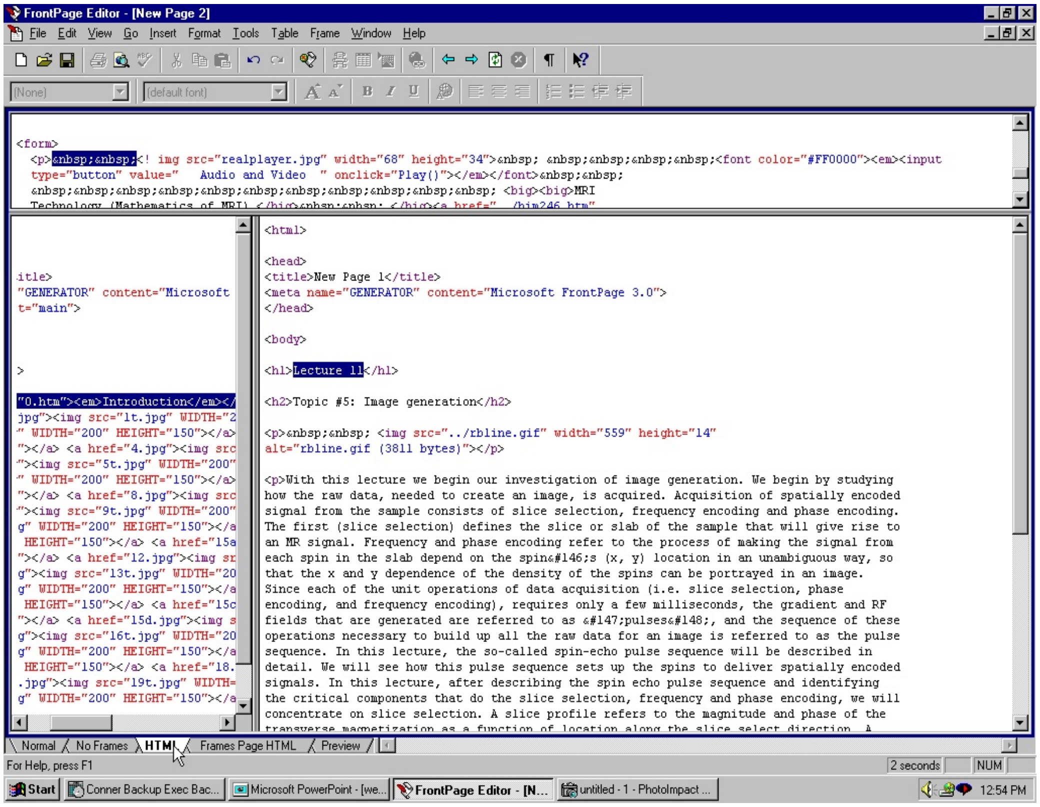

Fig.2: Microsoft Frontpage, HTML view for editing scripts.

The FastCap program provided with the AV Master board was used for digitizing the video. Prior to using FastCap, the sVHS video was viewed in its entirety, and the start and stop times of each page of the notes were recorded. A Panasonic Model 8650 sVHS recorder was used to obtain reliable time points and control over the video playback. Basically, after setting basic options to indicate the source media (e.g. NTSC), all one has to do in FastCap is toggle a button to start and stop the capture. One hardware compressed .avi file is created for each page of the lecture notes. You cannot run other processes on a Pentium II-266 computer during the capture, or writing to the SCSI AV hard disk will be interrupted.

This slide shows Adobe Premiere with the video dragged into the construction window. We use Adobe Premeire to output a standard avi file for RealPlayer. The RealPlayer Encoder cannot read the hardware-compressed avi file from FastCap. Figure 3 shows Adobe Premiere with the FastCap avi file, and a copy of this file, dragged into a construction window for processing.

Either 160 x 120 or 320 x 240 resolution videos were produced in Adobe Premiere, with monoaural 11.2 KHz bandwidth audio. The program has a large number of output options, including video compression versus video image quality settings, and blur settings to remove sharp edges that resulted in reverberation lines in the compressed files. We did not change many parameters for digital video appearance optimization. The main problem with the video was reverberation lines eminating from high contrast edges, and this was reduced using gaussian blurring prior to compression. The blurring reduced video quality of the Premiere avi file, but resulted in improved output from the RealPlayer Encoder.

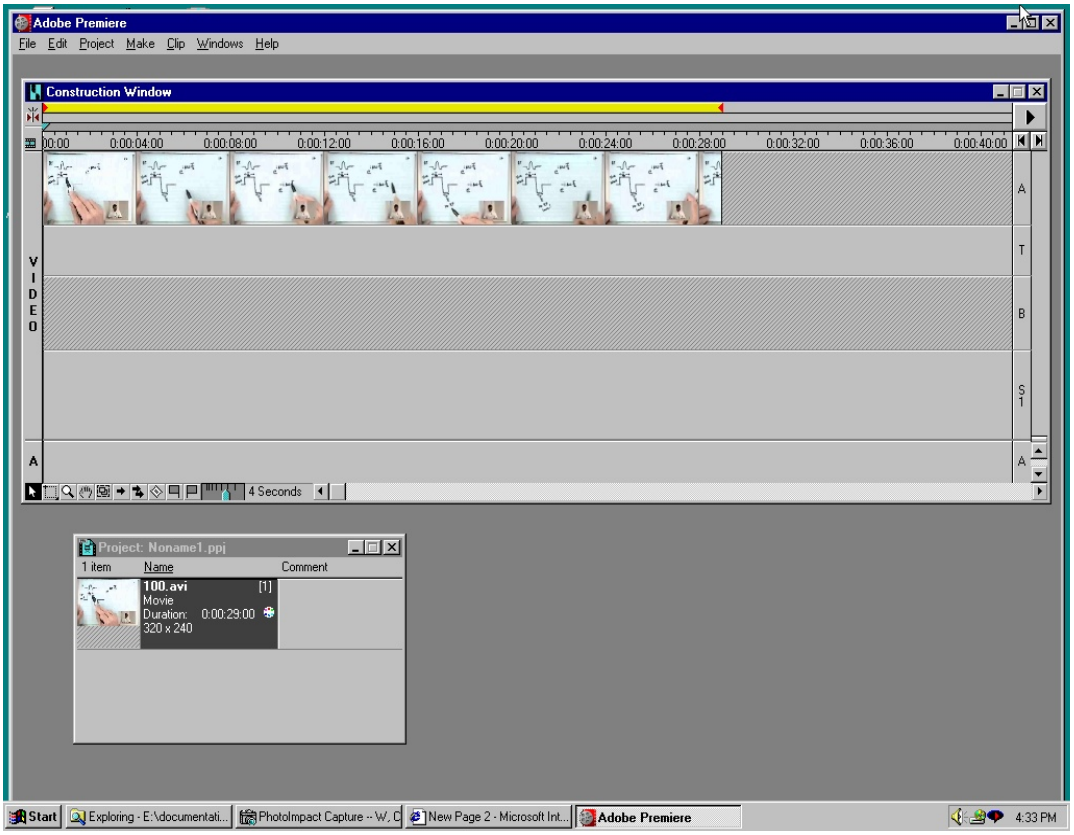

Fig. 3: Video Editing in Adobe Premiere

The RealMedia Player allows Web browsers to display streaming video. The streaming video file is not downloaded to the hard drive, but instead is buffered in memory and displayed in real time. The streaming video must be created in the RealPlayer format. The Realplayer Encoder can produce a wide range of video and audio quality and file sizes. There are options for optimization based on content, for example if the video is of “talking heads” type, this can be specified. The RealPlayer Software Development Kit (SDK 3.0) was necessary to convert the .avi file from Adobe Premiere to a compressed video (.rm) file. The available audio and video input formats were: 16-bit mono or stereo audio data in PCM format, Audio sampling rates of 8, 11.025, 22.05, or 44.1 kHz, and 24 bit-per-pixel (RGB) video data. The RealPlayer Encoder API output formats were 6.5 to 80 Kbps (thousand bits per second) audio, content optimized (e.g. talking heads), and 7 to 96 Kbps video, content optimized.

The Avicnvt program provided in the SDK does the conversion. The “6.5 Kbps Voice” option used in the Avicnvt program specified an “Audio option for speech or video based content with speed and background music over 28.8 Kbps modem”. Believing that Network connections would be slow, we specified the “low-end” video and audio output format “6.5 Kkbps Voice” which resulted in the smallest RealPlayer files.

Digital Audio

For the Audio used in the Current Concepts Classes, Adobe Premiere worked for conversion from the FastCap output, but SoundForge was the preferred program. SoundForge allowed direct creation of the RealPlayer file, so the avicnvt program was not needed. SoundForge provided detailed visualization of the sound file. Typically, the entire 1 hour 20 minute lecture was digitized (using FastCap) and loaded into SoundForge, then cut into segments in accordance with student-supplied lecture notes. The program also provided processing to improve the audio quality. Within SoundForge, the audio file from FastCap is normalized, compressed and output to RealPlayer (.ra) format file.

Normalization of the audio insures that over segments of the audio, the dynamic range of the audio representation in your output file is being fully utilized. Compressing the audio is recommended to reduce file size and actually improves the audio quality, by optimizing the 16-bit representation of the audio to better handle conversion to 8 bit that is performed by the RealPlayer Encoder.

The students did not use microphones when they asked questions, and these questions were inaudible in the original tape. SoundForge allowed increasing the volume of these segments. Figure 4 shows a question in the original file as a low amplitude section, and this section has been selectively amplified so that it is audible. These sections of low intensity were manually identified and amplified one-by-one. SoundForge did not provide automatic detection of these sections.

Digitized Lecture Notes

Student handwritten lecture notes were used for the Current Concepts classes, but the scanned pages using the default settings needed improvement. The major problem was that the writing was too light for the scanner to capture unbroken lines, making reading of the text extremely difficult. Histogram normalization and despeckling significantly improved the readability of the text. First, the default scanned image was converted using the “line art” setting with an optimal threshold determined by trial and error for each lecture page. A threshold low enough to improve the line continuity also produced a lot of speckles in the image. Adobe Photoshop was used to reduce the number of speckles in the image via a median filter. The result was not only a reduction in the number of speckles, but also an improvement in the continuity of the text lines. Figure 5 shows comparison of two different scanner settings. The top left image is the regular color scanner output. The bottom left image was scanned using the “line art” setting with a relatively high threshold, which was set by trial and error. The images on the right show before and after de-speckling using a median filter in Adobe Photosho

Digital slides

Slides used in the Introduction to MRI in Biomedicine course were digitized using a Polaroid Sprint Scan 35 Slide Scanner at very high resolution and stored on CDROM. Digital slide production parameters were as follows: Scanner Resolution: 2700 dpi, Output: 3904 x 2680 @ 2700 dpi, Color Correction: Remove Cast, Grayscale: 9.98 MB, Color: 29.93 MB. The large file size was not practical for Web presentation. They were converted to low resolution 640 x 480 jpeg images for the web site main screen, and 160 x 120 jpeg images for the left scrolling window.

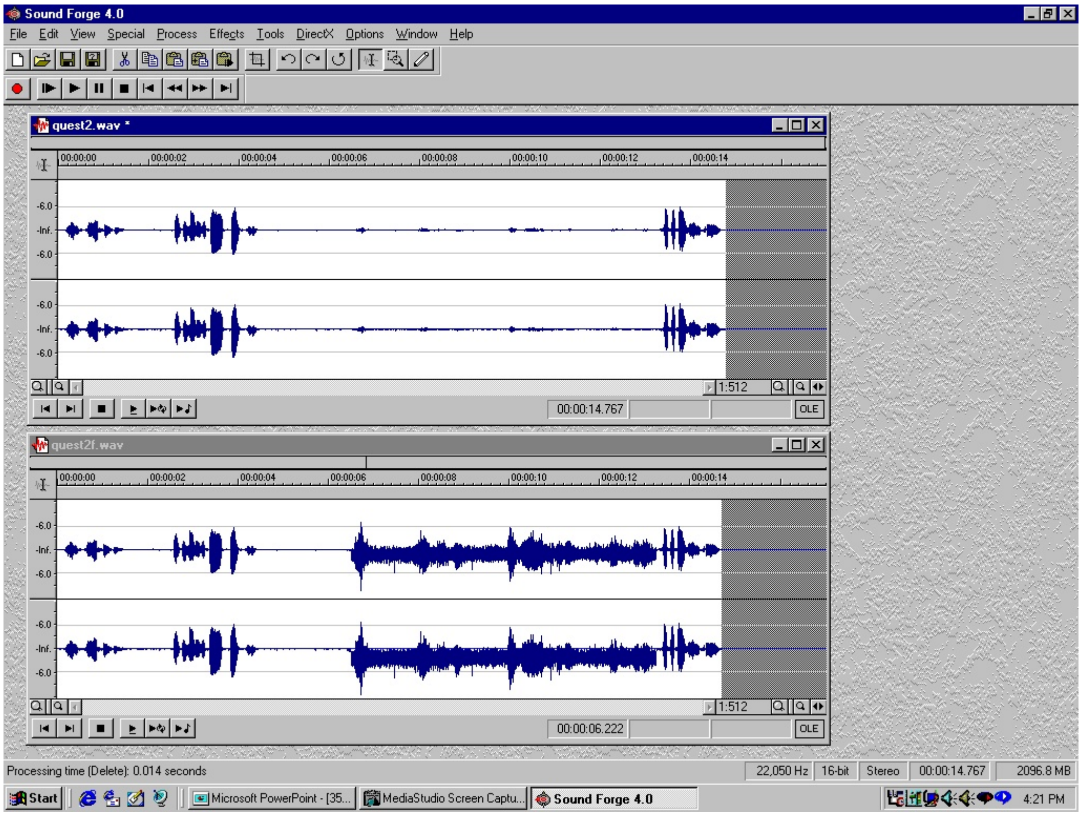

Fig. 4: Editing audio files in Sound Forge

HTML details

As mentioned earlier, Frontpage did the straightforward layout of the Web site, but HTML was coded directly for some features, in particular password protection for the links to the course materials, and button features. For example, the HTML code segment for defining a button to play an audio file is shown below. A form defines the space within which several items can be put, such as buttons, blanks, titles etc., anything between <! and > is "comments", colors in html are in hexidecimal values, with "#FF0000" signifying black. The <em> symbol is for emphasized text, <p> specifies the beginning of "paragraph", and “input” tells the browser that the user interaction will occur. In this case, the interaction is clicking on a button. The parameter “VALUE” is the text typed on the button, “onclick” defines the hyperlink to the RealPlayer audio file 17A.ra, activated with button press, and "parent.main.location" declares that the linked-to file it is in the same folder as the script. The following segment of Javascript code provides two buttons with links to audio:

```
<form>
<! img src="realplayer.jpg" width="68" height="34">
  <font color="#FF0000"><em><p><input TYPE="button" VALUE="Audio#1: P.72"
  onClick="parent.main.location='17A.ra'"></em></font>
```

```
<! img src="realplayer.jpg" width="68" height="34"> <font
color="#FF0000"><em> <input  TYPE="button" VALUE="Audio#2: P.73"
onclick="parent.main.location='17B.ra'"></em></font></p>
</form>
```

For BIM 246, a single button was used to activate the video, and which video was selected depended upon which lecture page was shown enlarged in the right frame of the browser. This dependency could not be implemented graphically using Frontpage tools. The link to the video contains a short Javascript to define a variable and a function, where var temp= the variable temp is assigned the name of the document (these are mostly jpg files) in the right hand frame of the browser, and the function Play() links to the file within this folder that has the same name as temp with a .rm appended to it.

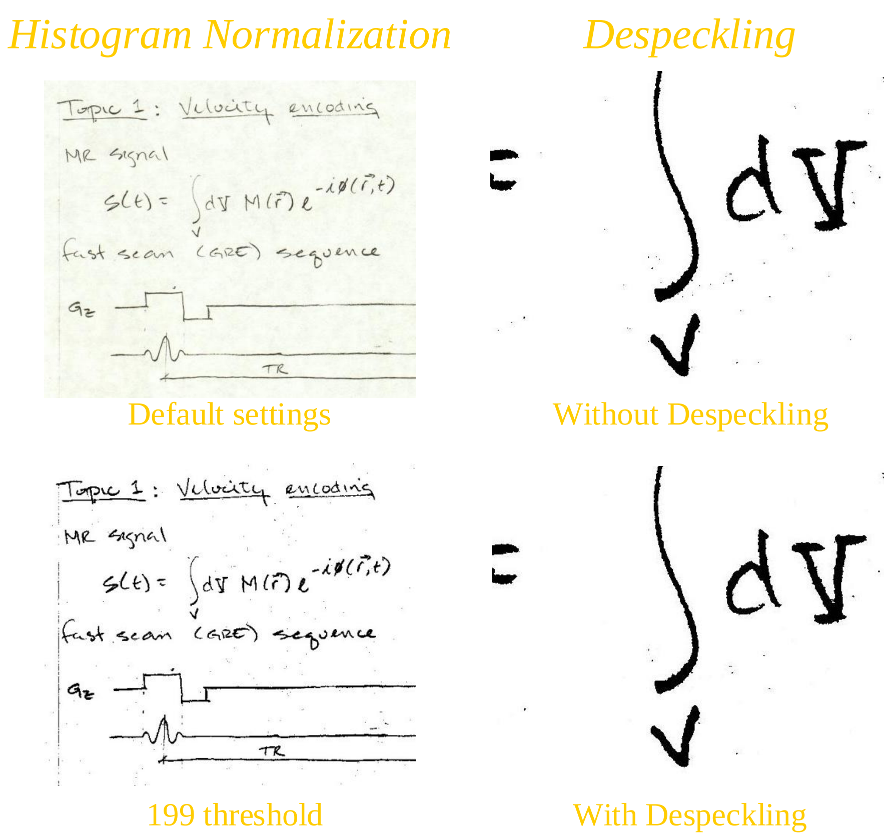

Fig. 5: Scanning and image processing of lecture notes.

The rest is essentially the same as the link to audio described above. Instead of opening a direct hyperlink, in this Form "onclick" starts the Play() function which starts the appropriate .ra file whose head name has been defined in the temp variable. The following segment of Javascript provides this link to video and audio link.

```
<script language="JavaScript">
<!-- Hide this script from incompatible Web browsers!
function Play(){
var temp;
```

```
temp=window.parent.frames['main'].location.href;
window.parent.frames['main'].location.href=temp+".rm";
}
<!-- -->
</script>
<body>
<form>
  <p><! img src="realplayer.jpg" width="68" height="34">
<font color="#FF0000"><em><input type="button" value="   Audio and Video  "
onclick="Play()"></em></font> </form>
</body>
```

Access to the course material is restricted using a filename strategy from ISN Toolbox, Inc. If the user does not enter the correct password, no html file of the name that the user typed will be found. The file password.htm is an identical copy of the Courses pages, except that the hyperlinks are in place. If the user types the correct password, the html file by that name (and containing the links) is displayed. Two variables are defined: suffix = the extension that will be added to the password to find the file, and pass_msg = text message to inform the user on the Courses page that they need to enter a password. The function go_there() takes the word that the user types in the blank, adds the suffix (.htm), and links to the file with that name. Note that there are two input types. One is the button, which is the same as before. The other is the "password" which is the blank for the user to enter text. The   denotes a hard space. The following segment of Javascript code provides this access restriction on the "Courses" page.

```
<script language="JavaScript">
<!--
var suffix = ".htm"
var pass_msg = "Enter password for access to links:";
function go_there() {
 location.href = document.pass_form.pass.value + suffix;
}
document.write('<form name="pass_form" onSubmit="go_there();return false">'
 + pass_msg + '<br><input type="password" name="pass" size="20" value="">'
 + ' <input type="button" value="OK" onClick="go_there()"></form>');
// -->
</script>
```

III. Results

This section will review the educational content of the web site. The courses in MRI are the main attraction of the site (Figure 6). There are six Courses offered in the curriculum. Introductory courses include *Introduction to MRI in Biomedicine.* Experimental courses include the *MRI of Biological Materials*, and *Practical NMR,* and theoretical courses include *MRI Technology* and *Current Concepts in MRI (two quarters).* These overlap in content somewhat but emphasize either the biomedical, biological or agricultural engineering applications. The Introduction to MRI in Biomedicine consists of 20 biomedically-oriented one hour lectures using over 1200 35 mm slides. The two experimental courses address practical issue of operating an MRI system in a biological or food science laboratory, and the three theory courses cover the fundamental physical science, biophysics and engineering of modern MRI devices and methodologies. For development of the advanced lectures in the theory courses, some of the most mathematically rigorous papers in the MRI literature were used.

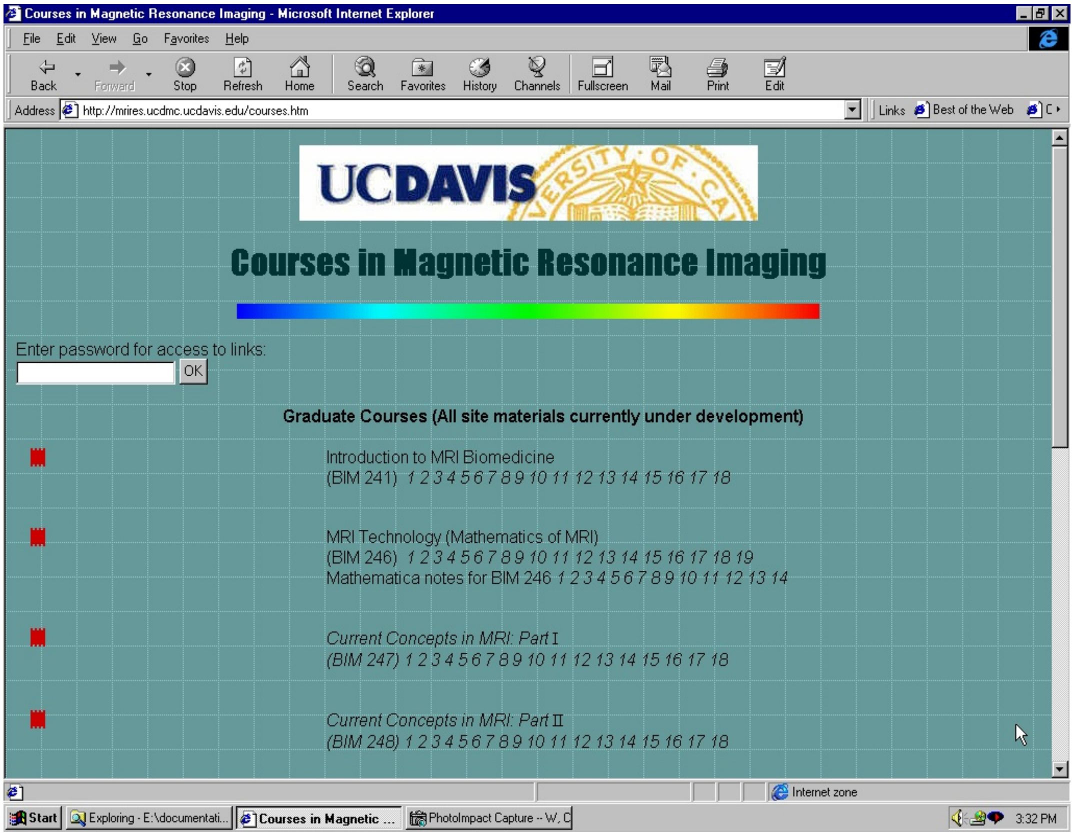

Fig. 6: "Courses in Magnetic Resonance Imaging" page on the Web site provides access to all course materials.

MRI Technology

The sequence of courses, BIM 246, 247, and 248 represent a full year of highly technical and quantitative study that prepares the student for graduate level research in MRI. In the first of these, BIM 246, entitled MRI Technology, MRI theory is covered using quantum mechanics, the Bloch Equation is derived from that, and the Bloch Equation is then used to understand and derive the equations for the more practical engineering aspects of image generation and reconstruction. Specific lectures in the MRI Technology include The Larmor Equation, Equilibrium Magnetization, The Schrodinger Equation, The Bloch Equation, Theory of Relaxation, and Dynamic Equilbrium. From these, engineering details of Gradient and RF Coil Design, Slice Selection, Spatial Encoding, Tissue Contrast, and Artifacts and their Elimination are covered. Specific examples of the lectures, showing the navigation of the Web site, are described below.

Figure 7 shows Lecture 16, which discusses image reconstruction. The user clicks on the number on the "Courses" page to get to this page. On the left, the user can scroll on the left frame to see all the pages of the lecture, so the user can easily search for a particular page. Each lecture has a written summary of the lecture content. Double clicking on a page icon in the left frame brings that page up in the right frame where it can be easily read, and clicking on the Audio/video button starts the corresponding digitized video recording. The resolution and overall quality of the video is low, but this was necessary to get a small file size deemed necessary for reasonable

Internet transfer speeds. As will be explained in more detail later, the RealPlayer encoder was used to convert uncompressed digitized video into the highly compressed RealPlayer format..

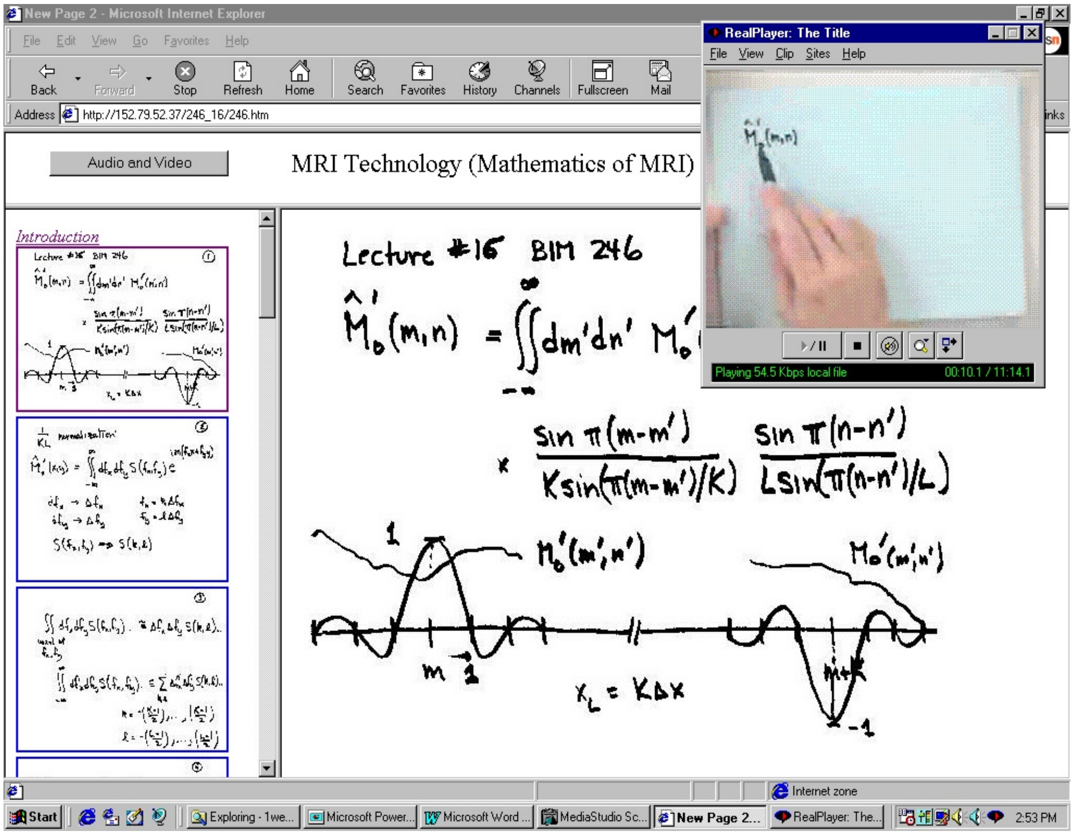

Fig. 7: BIM 246, Lecture 16, First page of lecture notes, with video window.

Figure 8 shows Lecture 7 of the MRI technology course. This lecture describes a molecular and tissue model that characterize the water compartments in tissues that give rise to the particular T1 and T2 relaxation times that we observed in MRI. In subsequent pages, a mathematical model is provided of water exchanging between the free phase and a bound phase in the hydration layer of a macromolecule. The model shows why the rotational characteristics of the water molecule determines T1 and T2 in each of the compartments, and how the fast exchange between compartments determines the overall observed T1 and T2.

The final lectures in this course describe the derivation of equations for steady state magnetization, which are so important for predicting the type of contrast, e.g. T1, T2, T2/T1, that will be obtained in a pulse sequence. Figure 9 shows a page of lecture 19, with the pulse sequence diagram below and the corresponding matrix equation, describing the evolution of the magnetization vectors, being derived from the diagram. From that large matrix equation, the equilibrium magnetization for the sequence is derived later in the lecture. Note that the video size is smaller here. Different sizes and resolution settings were tried, and not all videos got updated to the larger size that we now consider standard.

The MRI technology course is supplemented with lecture notes written in *Mathematica* (Figure 10). The strength of *Mathematica* is its ability to perform symbolic mathematics or numerical

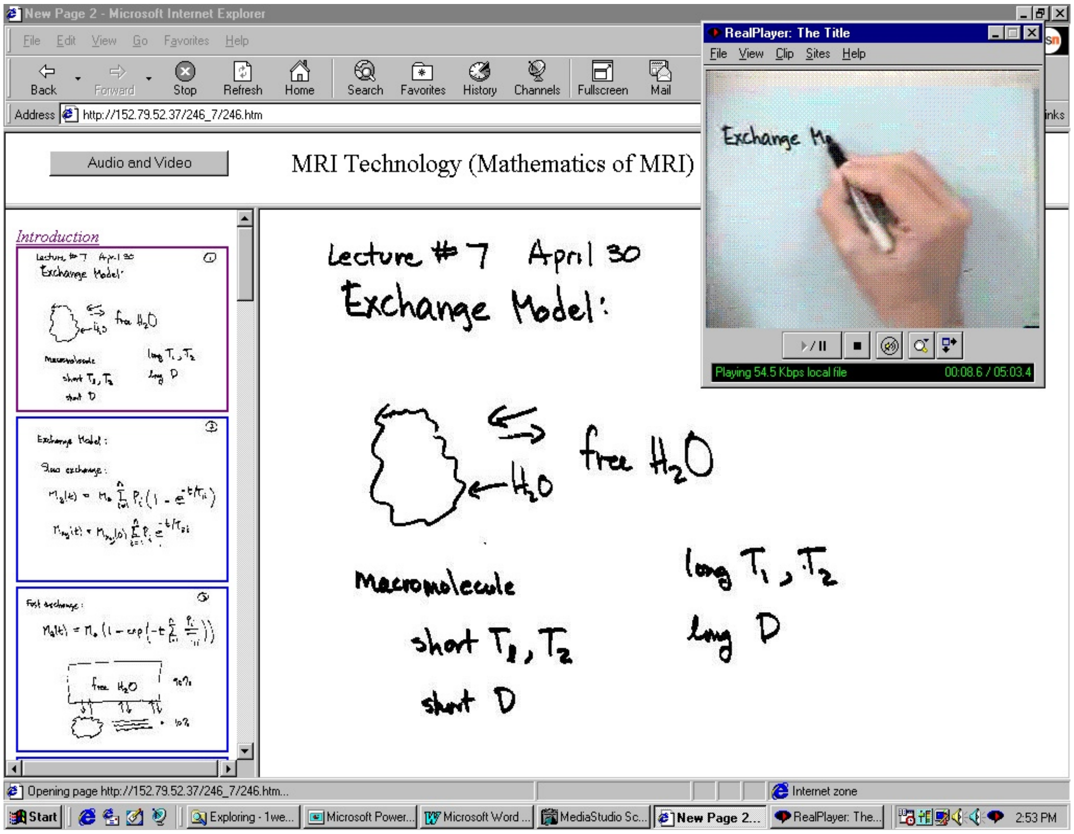

Fig. 8: BIM 246, Lecture 7, Molecular and Tissue Model of T_1, T_2 Relaxation.

analysis. In this regard, the goal is to allow the student to interactively explore the equations of MRI, by manipulating them, plugging in numbers, and seeing imaging results. The Mathematica files on the site provide a complete representation of the course, but we have not had time to implement any of the interactive features.

Introduction to MRI in Biomedicine

Not all students want to learn MRI with such a mathematical orientation. In fact, for the majority of biomedical engineering graduate students, “Introduction to MRI in Biomedicine” provides the necessary understanding of engineering, biological and clinical aspects. The format of this course is 35 mm slides, and have discussed the digitization of these slides in the Methods Section. All the basic MRI physics is covered qualitatively, without Quantum Mechanics or the Bloch Equation. Many images are shown, and the importance of MRI in clinical diagnosis is emphasized. Specific engineering lectures include Spin and Signal Concepts, MR Hardware, Image Generation, Image Contrast, Scan Parameters, and Artifacts and their Elimination. Biology/Clinical lectures include Brain Imaging, Biophysical Basis of T1 and T2, and MR Safety.

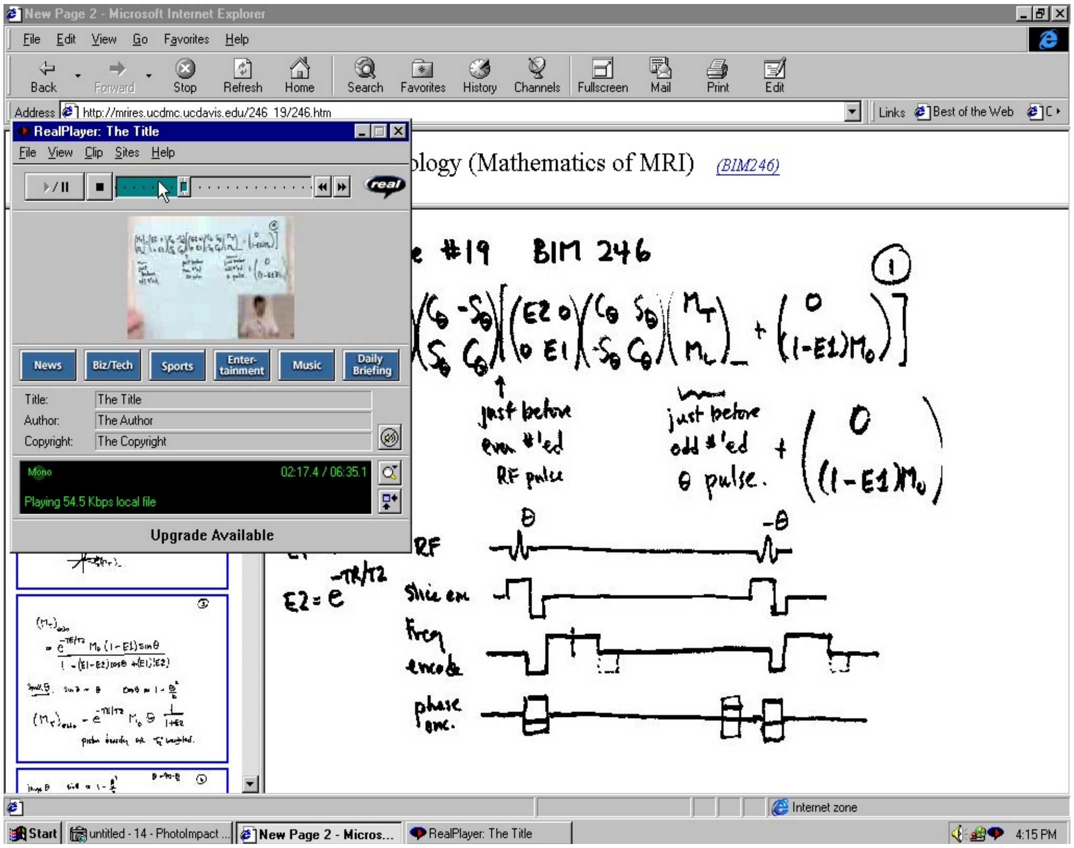

Fig. 9: BIM 246, Lecture 19, Gradient Recalled Echo Sequence: Magnetization evolution and dynamic equilibrium.

For example, Figure 11 shows Lecture 12, which is entitled Appearance of Hemorrhage. This lecture goes through the evolution of the changing MRI signal intensities in the hemorrhage due to the different blood products. This lecture provides a good example of the complexity of the MRI signal in tissue. The page layout is the same as in the other course. The user can scroll through small versions of all the slides in the left frame, double click to bring up the slide in the large right frame, and click on the video bottom to see the video. The video only shows the motion of the laser pointer. There is very little action in these videos (only the movement of the laser pointer), but the movement of the laser pointer is absolutely essential to follow along with the instructor, and the larger picture in the right frame provides a clear view of the slide.

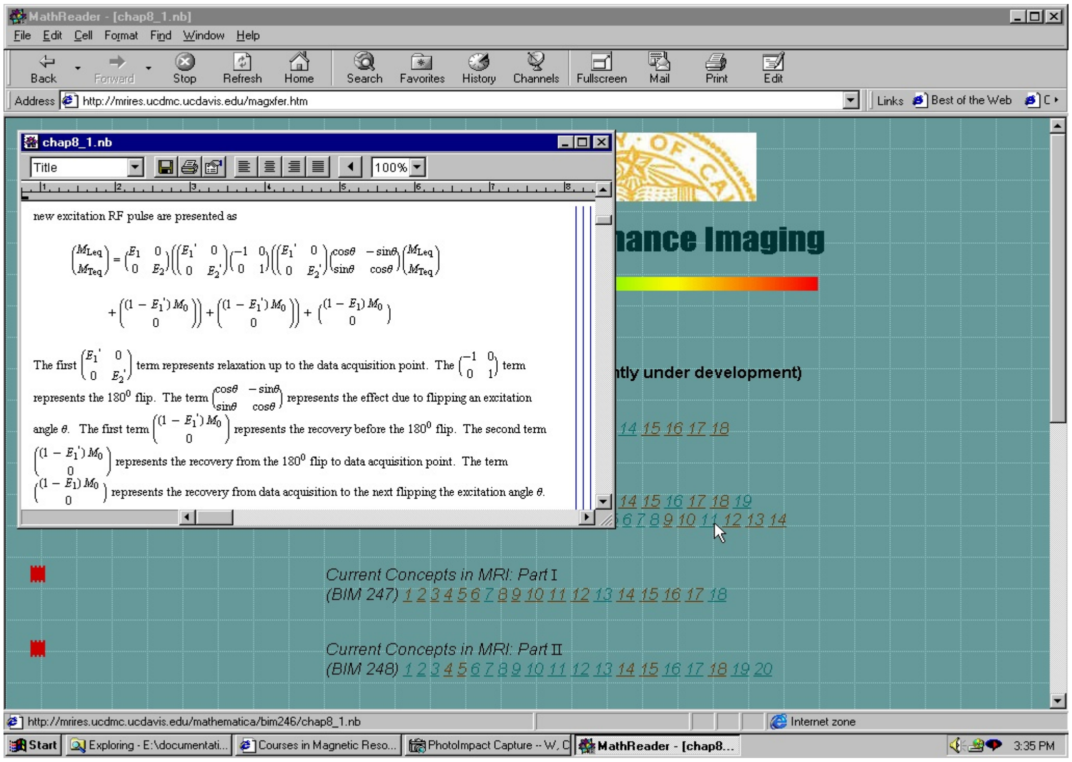

Fig. 10: BIM 246, *Mathematica* lecture notes on gradient recalled echo sequence: magnetization evolution.

Many of the students just want to know how to specify a scan on the MRI system for their experiments. In other words, they only want to know how to intelligently select the pulse sequence parameters. For this, in BIM 241 there are several lectures on Scan Parameters. Figure 12 shows explain Spatial Resolution in terms of the field-of-view (FOV) and matrix size. Both of these parameters are selectable from the operator’s console of the system. The change in the voxel size that results when the FOV is reduced is shown. This idea is then reinforced with images. This is the image obtained using an 18 cm FOV, and this is the image obtained with a 13 cm FOV. The student confirms that the scan parameter change does improve the spatial resolution (i.e. the observance of fine detail in the image), but also notes that the signal to noise of the smaller FOV (higher resolution) image is less.

Figure 13 demonstrates how Averaging (NEX) is used to improve signal-to-noise ratio. After discussing the method of repeating and averaging each data acquisition, two images are shown side by side, one obtained with 2 averages, the other with 6 averages, to show the improvement in signal to noise (seen as a loss of graininess), that is obtained with six averages.

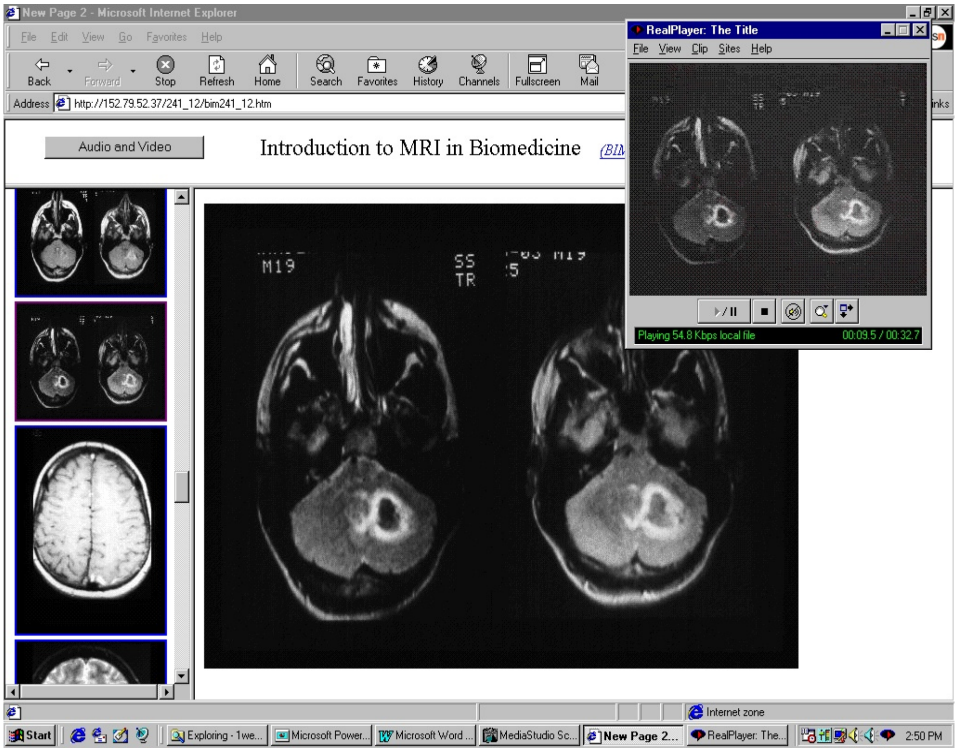

Fig. 11: BIM 241, Lecture 12 on Appearance of Hemorrhage.

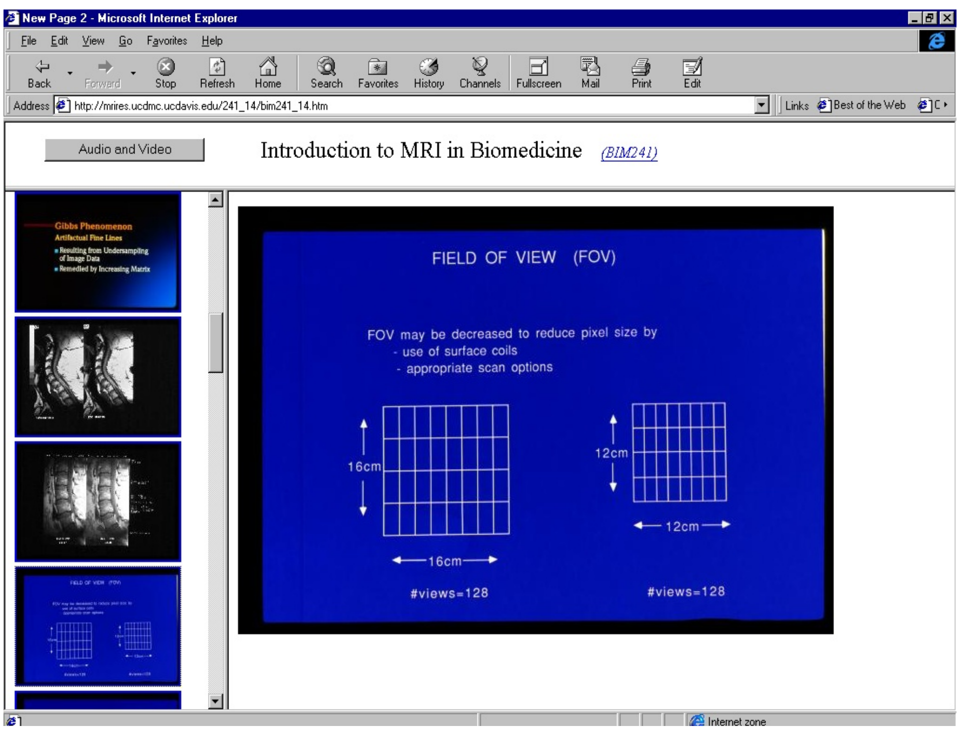

Fig. 12a: BIM 241, Lecture 14 on Scan Parameters: Dependence of spatial resolution on FOV.

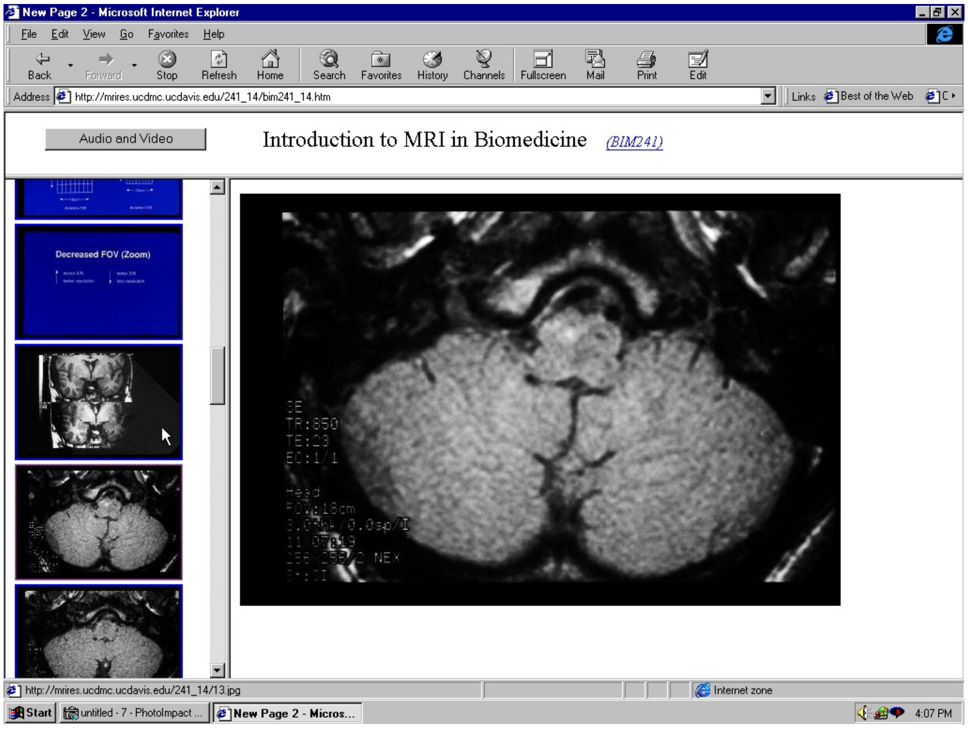

Fig. 12b: Image using FOV of 18 cm.

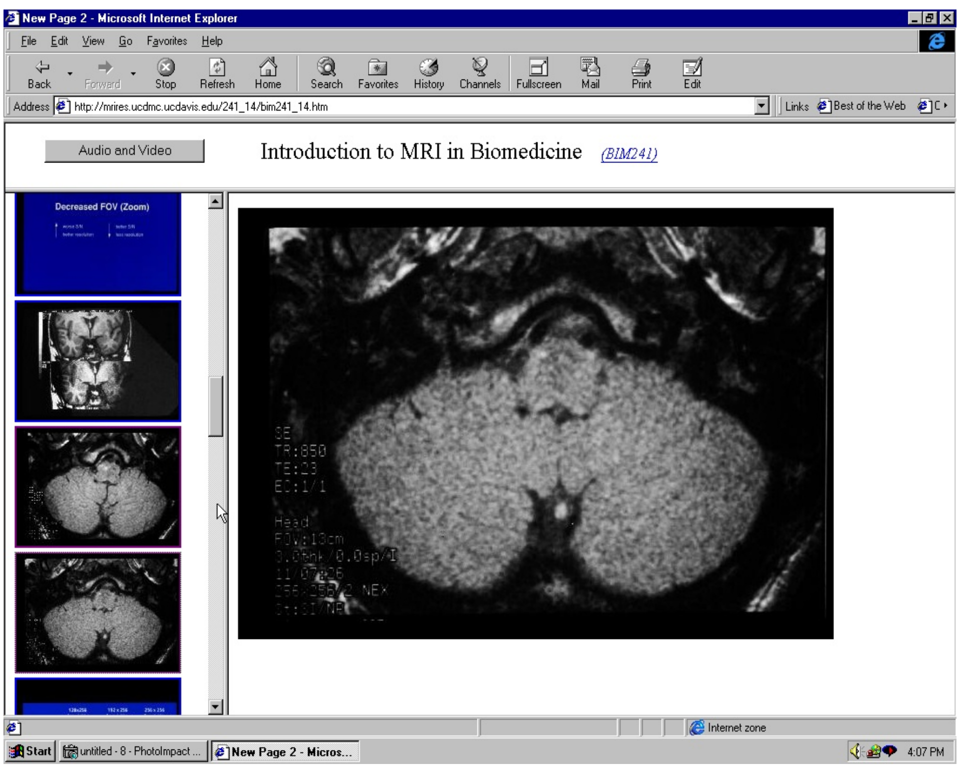

Fig. 12c: Higher resolution image using FOV of 13 cm.

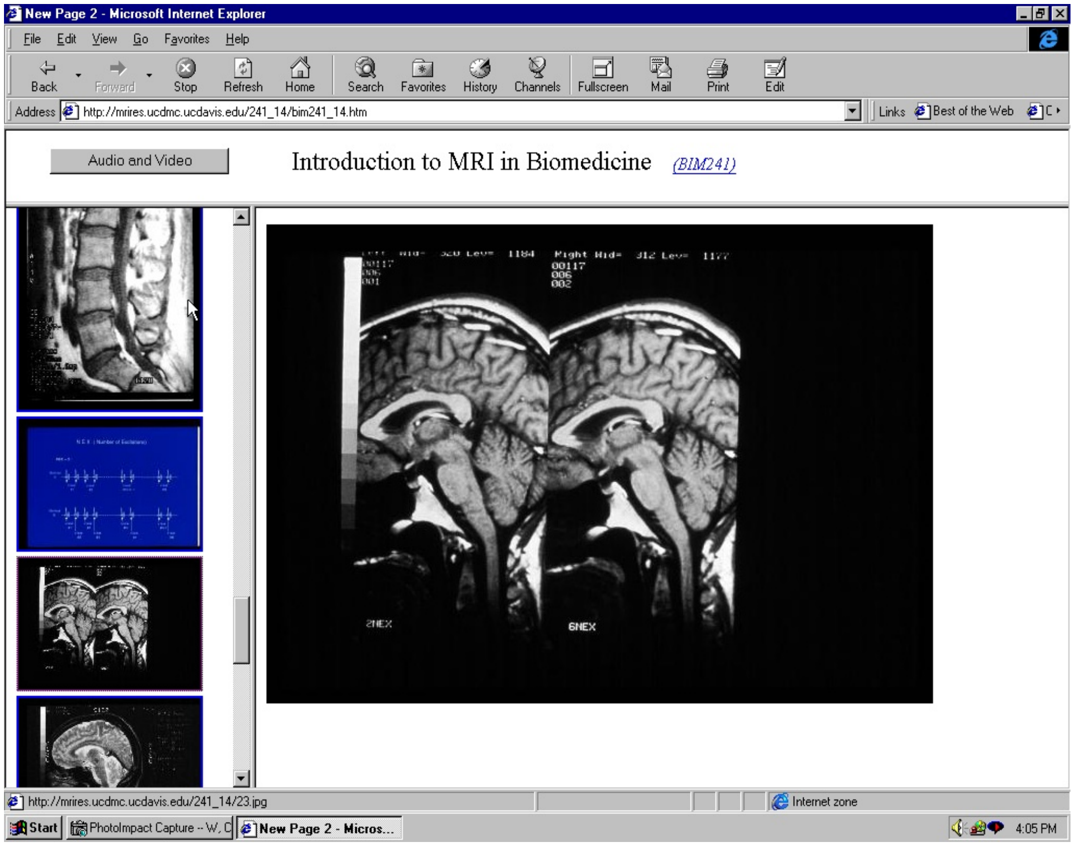

Fig. 13: BIM 241, Lecture 14 on Scan Parameters: Effect of repeated excitations and averaging on image quality.

The most difficult lectures of the course are those on phase encoding. The instructor has made great efforts to explain phase encoding with pictures, so that the students understand qualitatively how the magnetization vector is manipulated to spatially encode the data. This visual, 35 mm slide format greatly helps those graduate student that merely want to use the equipment with existing pulse sequences and processing methods, rather than develop new sequences and methods. Figure 14 shows one example from that lecture.

Current concepts in MRI

The "Current Concepts in MRI" courses are advanced courses designed for the medical imaging PhD candidate, and brings those individuals much closer to the state-of-the-art MR imaging and MRI basic science research. The MRI technology course is a prerequisite to these two courses, which are given over the remaining two quarters of the academic year. Specific lectures (or sets of lectures) in these courses included Velocity Encoding, Echo Planar Imaging, Spiral Imaging, Ghost Artifact Correction, K-Space Rebinning, Computer Simulation, Dynamic Equilbrium, RF Spoiling, and RF Pulse Design. These topics are covered in great mathematical depth.

These courses were taught for the first time last academic year, so only student lecture notes and audio tapes of the lectures are currently available. To organize the material on the Web site, each lecture was partitioned into several 5-15 minute segments, according to natural breaks in the discussion. Details of the digitization of the lecture notes and audio files have been discussed in

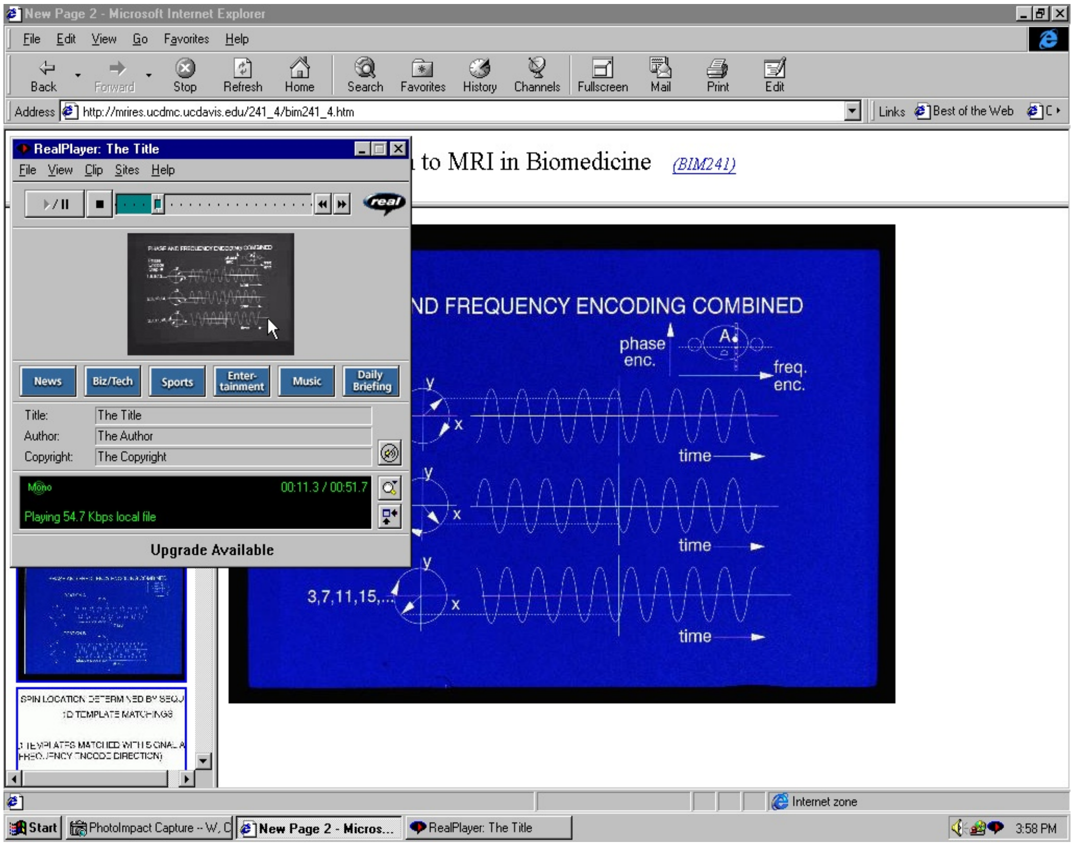

Fig. 14: Lecture 4 on Phase Encoding

the Methods section. As with the other lectures, the user can scroll through the pages, looking for points of interest. Clicking on a page icon in the left frame, brings a readable page up in the right frame, and clicking on the corresponding audio file button starts the audio.

Figure 15 shows the data acquisition method for Echo Planar Imaging being explained. Spiral imaging is a competing fast imaging technique that offers some advantages over EPI. Figure 16 shows the signal equation for the Spiral k-space trajectory. As with EPI, all aspects of the Spiral data acquisition, and image reconstruction, including rebinning of the raw data from the spiral acquisition to a cartesian (standard) acquisition, are presented.

Over the past 10 years of MRI development, there has been a proliferation of fast scanning methods, each with its own acronym such as SPGR, GRASS, FISP, FSIP, FAST, and CE-FAST. In Current Concepts, Part II, the evolution of magnetization that is induced in these different sequences is quantitatively modeled, and the differences in signal intensity and contrast that has made many of these sequences useful for clinical diagnosis, is revealed. For example, Figure 17 shows the pulse sequence diagram for a gradient echo spoiled sequence, and will write out the corresponding equations for magnetization evolution and the steady state magnetization.

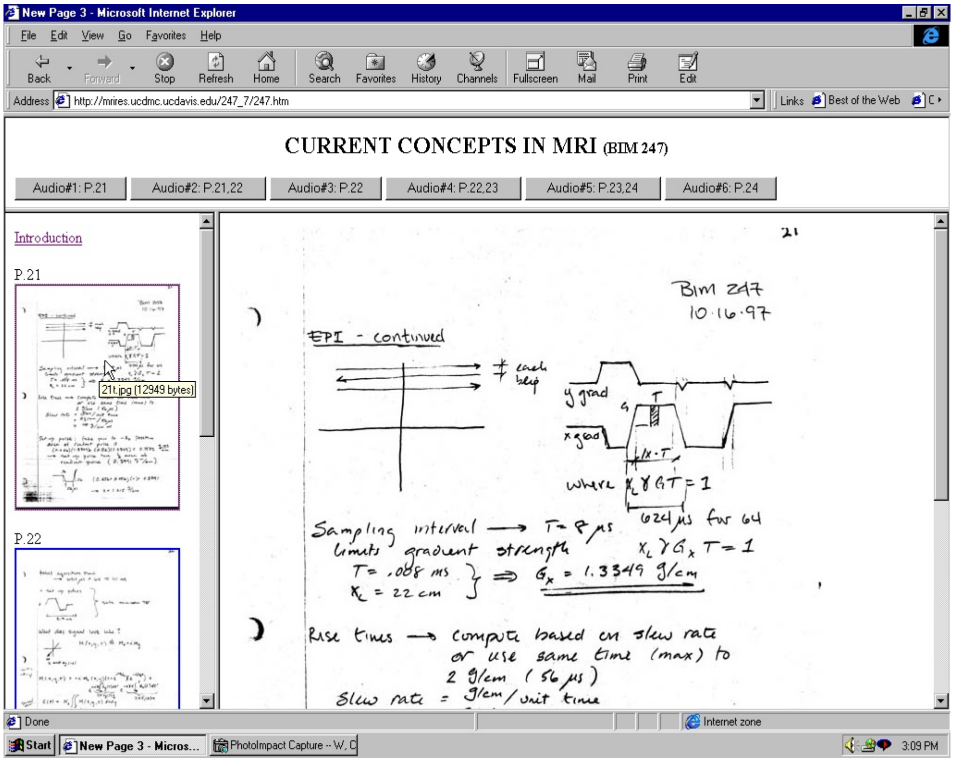

Fig. 15: BIM 247, Lecture 7, page 21, Data acquisition in Echo Planar Imaging.

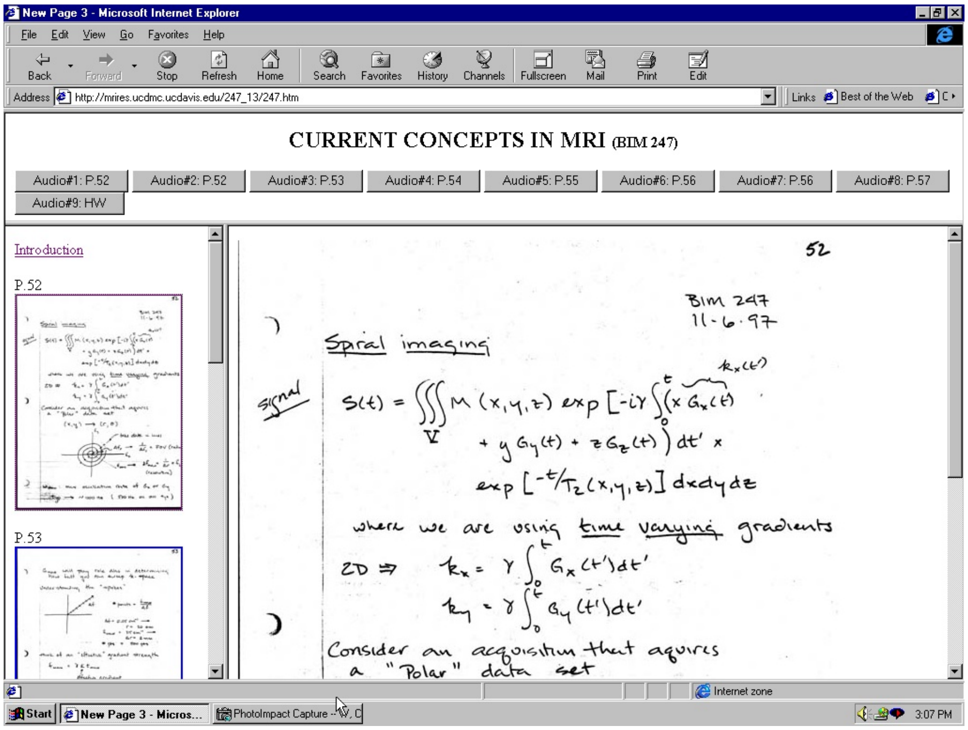

Fig. 16: BIM 247, Lecture 13, page 52, Data acquisition for Spiral Imaging.

The magnetization evolution is also studied entirely with pictures to help develop an intuitive understanding of these complicated pulse sequences. Figure 18 shows the pulse sequence and magnetization evolution for one of the so-called refocused gradient recalled sequence, characterized by gradient pulses that reverse the effect of the readout and phase encoding gradients, to increase the transverse magnetization.

Practical NMR

Two courses in the curriculum are not targeted toward biomedical imaging, but rather general NMR and industrial MRI. The Practical NMR course has both a laboratory and lecture component. For this course, a 103 page book of lecture notes is provided on the site in Adobe Acrobat format, as well as an instructional manual on use of a Bruker 7T small animal imaging system. The Laboratory component of the course focuses on the student obtaining practical experience on this 7T system. Topics include the Unix Operating System, Suntools graphical user interface, NMR Shell, getting and saving datafiles, processing and inspecting data, setting up data acquisition, selection and positioning of probes and coils, shimming, pulse calibration and gains, probe tuning, decoupling, saturation, imaging, data archival, and writing scripts for scan automation. The lecture component provides brief introductions to the following topics: spins and energy levels, pulsed FT experiments, rotating frame analysis, FID signals, complex signals, signal characteristics, and probe design & tuning. A specialized theory portion of the theory component provides a brief introductions to one or more of the following topics: nuclear coupling, solvent suppression, Nuclear Overhauser Effect (NOE), 2D NMR theory, 2D NMR experiments, MR imaging, and or localized spectroscopy.

The Laboratory course prepares graduate students to independently operate the spectrometers. It introduces the student to MR data acquisition on laboratory-grade instruments (which is quite a bit less automatic compared to a clinical imager), and takes the student through all the procedures that will be necessary. The lectures prepare graduate students for understanding modern NMR as it is applied to chemical analysis, in particular the analysis of macromolecules, with no particular emphasis on imaging.

MRI of Biological Materials

Food science and Technology has an emphasis towards understanding rheological properties of colloids and solutions relevant to food and pulp processing[3]. Their MRI course focuses on the theory and experiments of flow through porous media, diffusion, and turbulence measurements. Lecture topics include spin dynamics, theory of T1 and T2 relaxation, pulse sequence descriptions, quantitative MR measurements, the Bloch equations, localized spectroscopy, chemical shift, susceptibility, MR imaging, SNR, and spatial resolution. Specialized topics include diffusion in field gradient, restricted diffusion, flow measurements, acceleration, turbulence measurements, design of experiments, porosity, phase volumes, colloidal and cellular systems, and Rheology.

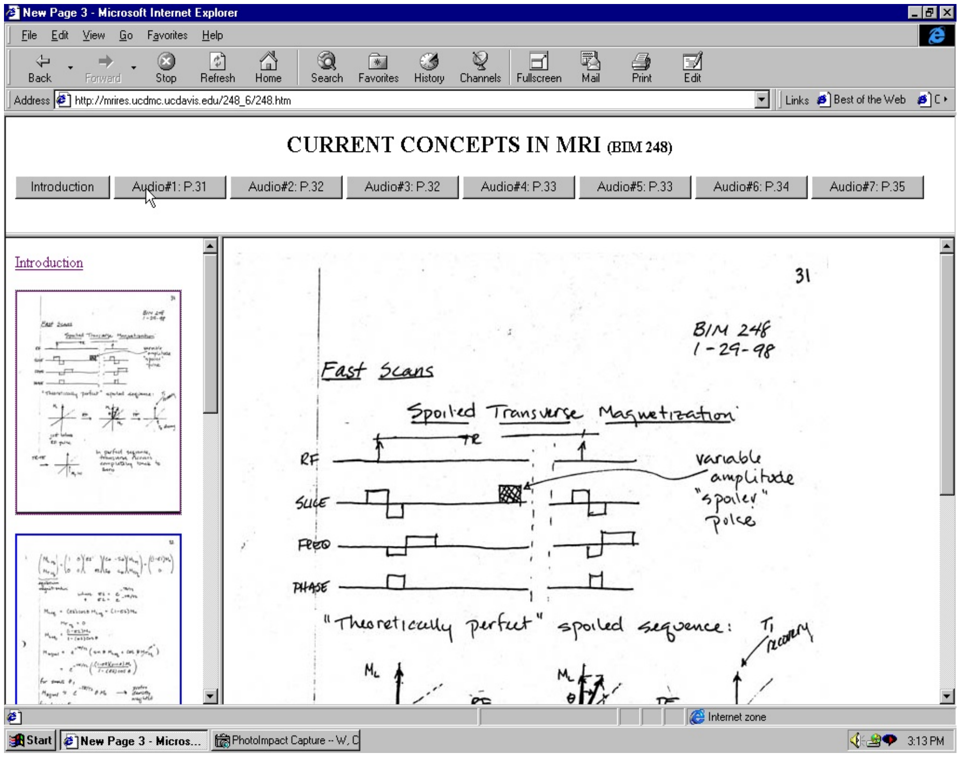

Fig. 17: BIM 248, Lecture 6, page 31, Dynamic Equilibrium in the "Spoiled" Gradient Recalled Echo Sequence.

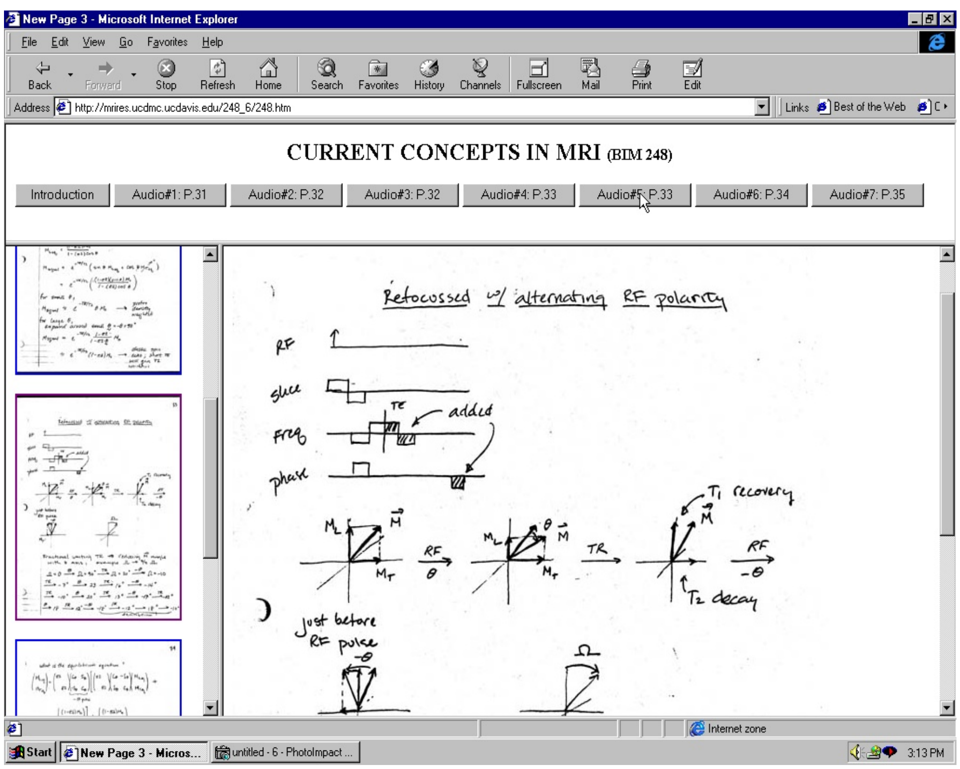

Fig. 18: BIM 248, Lecture 7, page 36, Dynamic Equilibrium in the "Refocused" Gradient Recalled Echo Sequence.

IV. Discussion and conclusion

The technology of Web site production is rapidly improving and thus it is virtually assured that a Web site will possess sub-standard materials. This Web site is no exception, and if done over, the video quality for example would certainly be improved in files of exactly the same size. However, we need only take the existing 320 x 240 compressed avi file and reconvert them using the latest software from Adobe and RealMedia. Also, while the RealMedia was used to create the streaming video files, Microsoft is offering a competitive streaming video product (Netshow) that may offer more consistent and seamless operation. The Web site is fulfilling a great need on the UC Davis Campus for MRI technical education, both basic and advanced, and over the next year it is our goal to have this site accessible nationally.

Bibliography

1. URL: http://152.79.52.37/

2. Stephan Wolfram, The Mathematica Book, 3rd Ed. (Wolfram Media/Cambridge University Press, 1996).

3. M.J. McCarthy, *Magnetic Resonance Imaging in Foods*, Chapman & Hall, New York 1994.

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