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Real-Time NMR Imaging Systems Using Personal Computers

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Two real-time NMR image-processing systems using high-speed personal computers have been developed. The first was made with a MS-DOS (Microsoft Disk Operating System) PC system (CPU, Pentium; clock frequency, 100 MHz) and a homebuilt frame memory board. The second was made with a MS-Windows (Microsoft Windows 95) PC system (CPU, Pentium; clock frequency, 133 MHz). The reconstruction time for one 128 × 128 image was 280 ms for the DOS system and 120 ms for the Windows system, while the image display time was 30 ms for the DOS system and 120 ms for the Windows system. NMR imaging experiments for observing unsteady particle or bubble motion in fluids were performed using these systems. These real-time image-reconstruction systems demonstrate great promise as add-on devices to existing NMR imaging systems.

INTRODUCTION

In the usual NMR imaging systems, the acquisition of data containing the desired information requires a few seconds to minutes and the image is usually not processed and displayed immediately but only after all the images have been acquired. However, there are several reports of the so-called ''real-time NMR imaging'' systems which enable real-time image observation by a combination of rapid image acquisition and a very fast image reconstruction and display (*1–7*).

Wright *et al.* (*1*) used an array processor directly connected to a commercial whole-body scanner with a specially designed digital interface to achieve an image-refresh rate of about one image per second for 128 × 128 pixel images, using a 10 ms repetition time gradient-echo sequence (GRASS), and named this technique MR fluoroscopy. Other approaches to real-time NMR imaging systems have also been reported: these include methods which use specially designed digital circuits (*4*) or workstations (*5, 6*).

Although all of the published systems (*1–7*) have enough processing speed for real-time NMR image reconstruction and display, most have some shortcomings if the goal is to develop a real-time image-reconstruction system which can be easily constructed and connected to any NMR imaging system. The main problem is that it is difficult to adapt such systems to generic imagers because they use special hardware and/or software. Furthermore, when a UNIX workstation is used for real-time image reconstruction, it is difficult to synchronize the reconstruction and display with the NMR system, because the UNIX operating system is not a real-time operating system.

An image-refresh rate of about seven images per second for 64 × 64 pixel images was reported by Kose and Inouye (*3*), who used echo-planar imaging (EPI) and a digital signal processor (DSP). Their image-processing system was connected to the NMR system with only three analog signal lines, which makes the system more suitable as an add-on device for any NMR imaging apparatus (*7*), and this was demonstrated later with a Bruker Biospec system. In the present paper, we report two real-time NMR imaging systems using high-speed personal computers to further meet the above requirements. To evaluate their system performance, NMR imaging experiments for observing unsteady particle and bubble motions in fluids were performed. The results demonstrate great promise for these add-on real-time NMR imaging systems.

IMAGE-RECONSTRUCTION SYSTEMS

Figures 1 and 2 show block diagrams of the two real-time NMR image-reconstruction systems developed in this study. The system shown in Fig. 1 was made on a MS-DOS (Microsoft Disk Operating System Version 6.0) personal computer system (PC 9821Xa9, NEC) with a 100 MHz Pentium (Intel) CPU. The system shown in Fig. 2 was made on a MS-Windows (Microsoft Windows 95) personal computer system (XPS P133c, DELL) with a 133 MHz Pentium CPU.

The DOS system has a two-channel, 12-bit A/D, 500 kHz maximum sampling frequency converter board (ADM-8498BPC, Microscience, Tokyo, Japan) for NMR signal digitization and a homebuilt frame memory board for image display. The frame memory board has two image buffer planes (256 × 240 pixels in 8-bit gray scale) so that one can be refreshed while the other is displayed. This board has a NTSC video signal output for real-time image observation on a CRT display and long-time image recording with a VCR. The A/D converter board, CPU, and the frame memory

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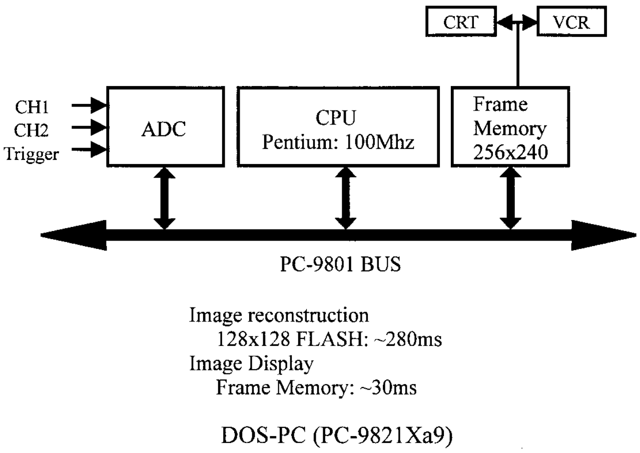

FIG. 1. Block diagram of the real-time NMR image-reconstruction system using a MS-DOS personal computer PC 9821Xa9. The 256 × 240 frame memory board has a NTSC video output signal for real-time image observation and long-time image recording. Reconstruction of a 128 × 128 image took 280 ms while its display took another 30 ms. Programs for data acquisition, image reconstruction, and image display were developed with Microsoft C compiler Version 6.0 and executed under MS-DOS Version 6.0.

board are connected with a peripheral I/O bus (PC-9801 BUS). The data-acquisition, image-reconstruction, and image-display programs were developed with Microsoft C compiler, Version 6.0, and the code was optimized to minimize the processing time and executed under MS-DOS Version 6.0.

The Windows system has a two-channel, 14-bit A/D, 1 MHz maximum sampling frequency converter board (PC-414G3, DATEL, Massachusetts) for NMR signal digitization. This board and the CPU are connected by ISA and PCI buses as shown in Fig. 2. NMR images of 128 × 128 pixels are displayed on a 256 × 256 pixel size window opened in Microsoft Windows. The data-acquisition, image-reconstruction, and image-display programs were developed with Microsoft Visual C++ compiler, Version 1.5. The code was optimized to minimize the processing time and executed under Windows 95 operating system.

EXPERIMENTS

Imaging experiments were performed using two NMR systems. The first one was a homebuilt system using a 4.7 T/89 mm vertical-bore superconducting magnet (Oxford Instruments) and a RF probe with an actively shielded gradient coil (Doty). This system was connected to the DOS image-reconstruction system with two output signal lines from the quadrature detector and a data-acquisition trigger line. The second system was a spectrometer/imager (Nalorac) using a 1.9 T/310 mm horizontal-bore superconducting magnet (Oxford Instruments), an actively shielded gradient coil (Magnex), and a homebuilt birdcage RF probe. This system was connected to the Windows image-reconstruction system with the same three analog signal lines as described for the DOS system.

Two MR imaging experiments were performed with the DOS system. In the first, 6.4 and 3.2 mm diameter nylon (1.1 g/cm^3) spheres were dropped through water mixed with cellulose to raise the viscosity and doped with $CuSO_4$ to shorten the proton T_1. Spheres were dropped into water in a vertical NMR tube (18 mm i.d. and 180 mm length) filled with the fluid and placed vertically in the RF probe. Then 128 × 128 pixel images were obtained and displayed as vertical slices containing the tube axis at 1.0 s time intervals using a FLASH sequence with 4.72 ms repetition time, 2.70 ms echo time, and 30° flip angle. In this sequence, 128 images were collected with 604.16 ms (4.72 ms × 128) used for data acquisition and 395 ms used for image reconstruction, display, and saving to the RAM drive of the DOS PC system. The data collection and image reconstruction were fast enough that selected spheres entering the imaging region could be brought into the 4 mm thick slice being imaged by rotating the NMR tube in the magnet while watching the image as shown in Fig. 3.

The second experiment was to study the flow of doped water in a loosely packed bed of spheres in an acrylic tube with a 17 mm i.d. The spheres were the same as those used in the first object, i.e., a mixture of 3.2 and 6.4 mm nylon

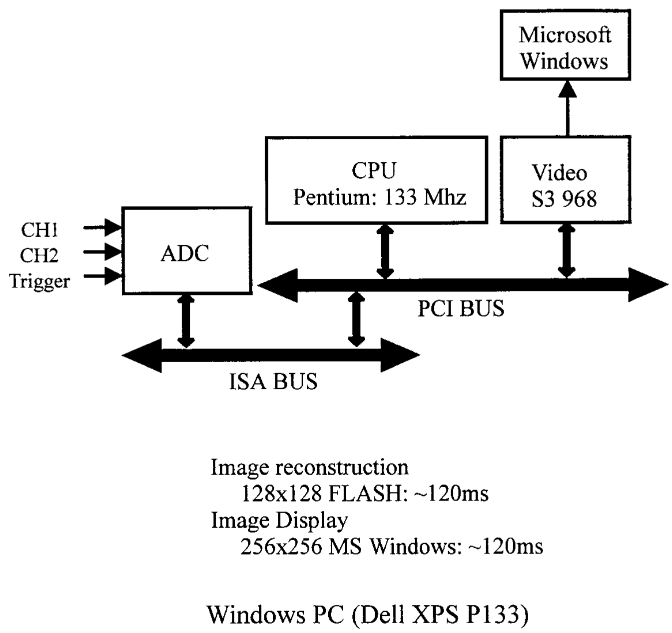

FIG. 2. Block diagram of the real-time NMR image-reconstruction system using a MS-Windows personal computer DELL XPS P133c. Reconstruction of a 128 × 128 image took 120 ms. Images are displayed in a window opened in MS-Windows; a 256 × 256 image required 120 ms. Programs for data acquisition, image reconstruction, and image display were developed with Microsoft Visual C++ compiler Version 1.5 and executed under Windows 95 operating system.

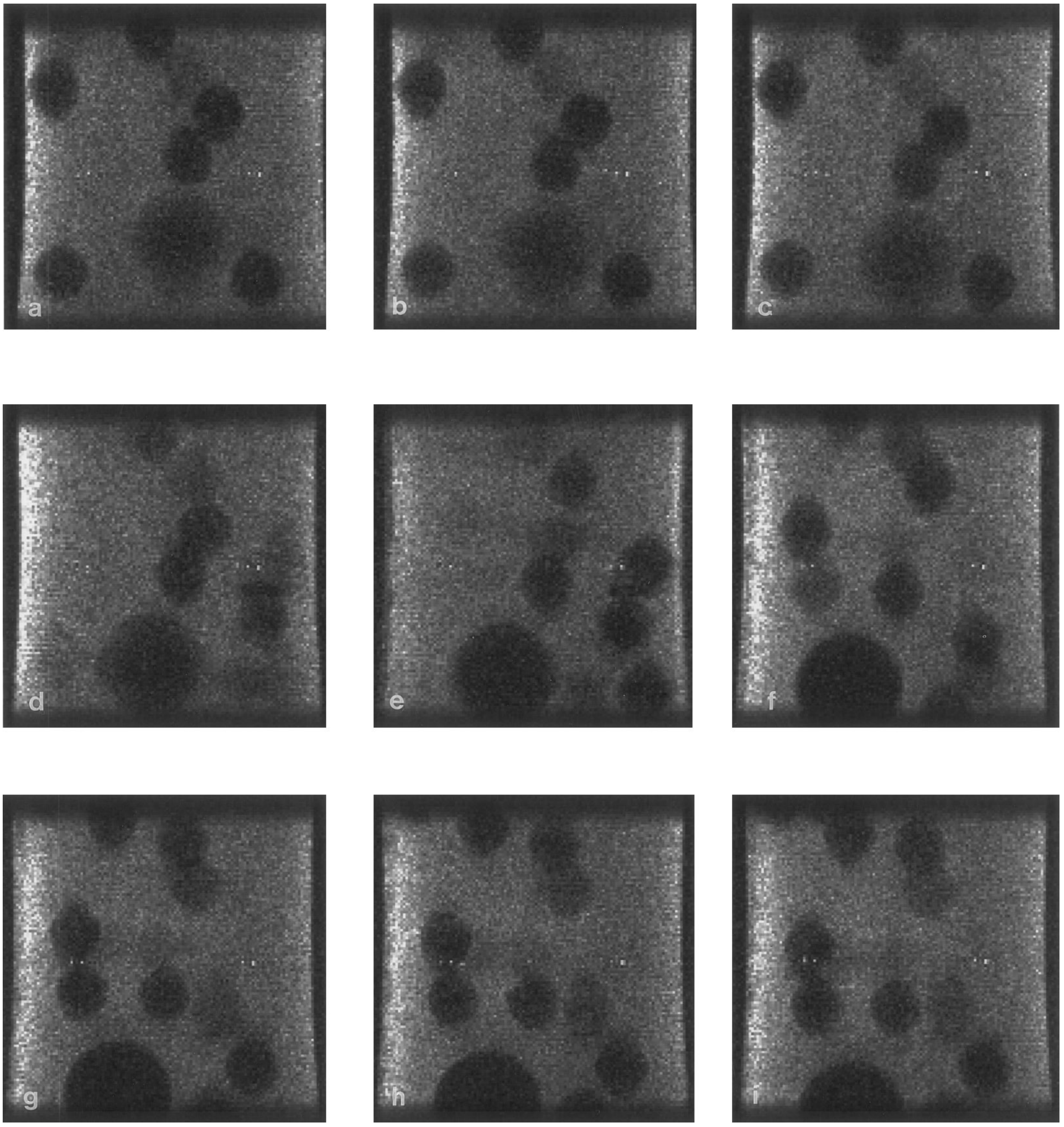

FIG. 3. Nine successive FLASH images of spheres falling through a viscous fluid recorded with the DOS system. The field of view is 19.2 × 19.2 mm, the slice thickness is 4 mm, and the successive frames are 1 s apart. The large sphere is almost out of the slice in frames (a)–(c) but in the slice in frames (g)–(i), after a controlled rotation of the test tube along the tube axis during frames (d)–(f).

spheres. The tube was placed vertically in the RF probe, as before, but the bottom of the tube was connected to a water container outside of the magnet with flexible tubing (Fig. 4) so that the water could be made to flow in either direction past the test section by raising and lowering the container. While the water level was raised or lowered interactively by watching the real-time display of the reconstructed images, a spin-echo EPI sequence (200 ms repetition time, 48 ms echo time) yielded 64 × 64 pixel images of a vertical slice containing the tube axis. In this image-acquisition sequence, 40.96 ms was used for data collection and 159 ms was used for image reconstruction, display, and saving to the RAM drive of the DOS PC system.

The capabilities of the Windows system were demonstrated by imaging air bubbles rising in a soap solution. A container was filled with Dial soap solution and a vertical needle for ejecting air bubbles was placed at the center of the bottle. The bottle was moved in order to place the needle in the 6.5 mm thick vertical slice while the real-time display of the NMR image was observed. Then 128 × 128 pixel

TABLE 1
Comparison of Real-Time Image-Reconstruction and Image-Display Times for Systems Using DOS and Windows Personal Computer Systems and Large- or Huge-Memory Models

	DOS 64 × 64 large (ms)	DOS 128 × 128 large (ms)	Windows 64 × 64 large (ms)	Windows 128 × 128 large (ms)	Windows 128 × 128 huge (ms)	Windows 256 × 256 huge (ms)
Image reconstruction	80	280	30	120	270	1170
Image display	30	30	30	120	120	490
Total	110	310	60	240	390	1660

slice images were obtained at 1.12 s intervals using a FLASH sequence with 6.0 ms repetition time, 3.0 ms echo time, and 30° flip angle, while air bubbles were created at the needle with a syringe. In this sequence, the data collection required 768 ms, and 350 ms was used for data transfer from A/D board to computer memory, image reconstruction, display, and saving to the hard-disk drive of the Windows PC system.

RESULTS AND DISCUSSION

Execution Times for Image Reconstruction and Display

Execution times for the image reconstruction and display were measured with a C program timer function for 100 repetitions and are summarized in Table 1. The Windows 95 system is multi-tasking and the measured time includes the overhead associated with this operating system. The measured times are those one would incur in actual use. The execution times also depend on compiler options; the DOS system used 16-bit 80286 code while the Windows system used 32-bit 80386 code. The execution time also depends on whether a large-memory model or a huge-memory model is used with the compiler. The large-memory model allows faster access to data less than 64 kbytes in size. If the array size increases beyond 128 × 128, we require more than 64 kbytes of memory for data storage and must use a huge-memory model. In going from the large- to the huge-memory model, the calculation time for image reconstruction approximately doubles while the image-display time is not significantly affected.

The time required for one 128 × 128 image reconstruction was about 280 ms for the DOS system and 120 ms for the Windows system. The large difference in the processing time between these systems may be due to differences in the machine codes used in the execution programs; the DOS system used 16-bit 80286 code while the Windows system used 32-bit 80386 code.

On the other hand, the time needed for image display was about 30 ms for the DOS system and 120 ms for the Windows system. In the DOS system, 30 ms is reasonable because the frame memory board requires one 16-bit address and one 8-bit pixel value data to display one pixel. In the Windows system, however, the image-display time is much longer than that of the DOS system, even though the video board is connected to the CPU with a very fast bus (PCI bus) having a data-transfer rate of 40 Mbytes/s. This may be due to some complicated process in the Windows Application Program Interface (API) functions used in the display program.

When the data matrix size is doubled, the image-reconstruction and image display times increase by about four times. With the programming tools we have used, there is a distinct advantage in restricting our data size to 128 × 128 as it allows a large-memory model to be used. At present a data size of 256 × 256 with a huge-memory model requires a data-processing time of 1.7 s/image. The time for saving onto disk was negligible compared to other processing times. For a 128 × 128 image the data save time was 5 ms. Our computer has 48 Mbytes of memory and the operating system uses disk caching which probably makes the write to disks very fast.

Comparison between DOS and Windows Systems

The main advantage of DOS is that programming is simple and straightforward. However, an additional image-display card is required for rapid image display, because image display with DOS function calls is too slow. The main advantage of the Windows system is that no additional image-display card is required, but the programming is not straightforward. Thus, there are two choices: the DOS system is recommended when a display card for rapid image display is available, while Windows programming is preferable when the extra programming does not present a problem.

Reconstructed NMR Images

In the first experiment, the DOS image-reconstruction system was used with the vertical-bore magnet to make FLASH images at a rate of one image per second. Figure 3 shows nine successive images, of a total of 600 images, of spheres falling through water. The field of view was 19.2 × 19.2 mm and the slice thickness was 4 mm. The larger (6.4 mm diameter) sphere, which is just outside the 4 mm thick slice

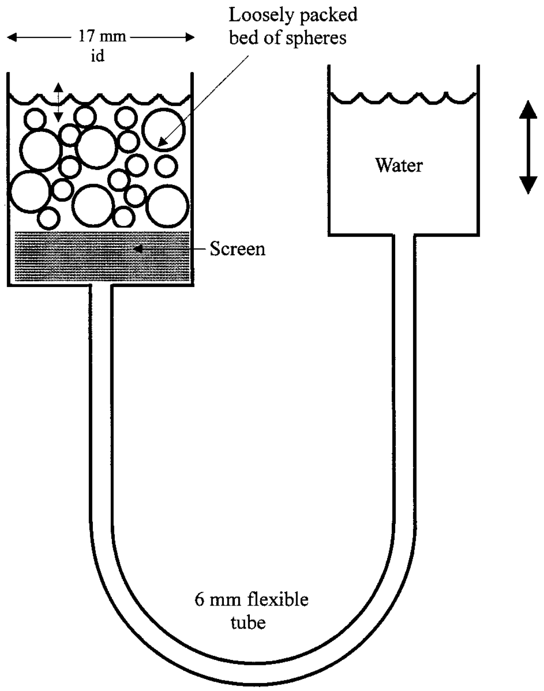

FIG. 4. Schematic diagram of the setup for flow through a loosely packed bed of spheres. Upward and downward flows through the bed were created by up and down displacements, respectively, of the water container outside the magnet.

in frames (a)–(c), is brought into the slice by a controlled rotation of the sample tube during frames (d)–(f). The combination of real-time image reconstruction and rapid imaging, as demonstrated, makes such interactive procedures possible using NMR.

The second experiment used the same reconstruction and NMR hardware to make echo-planar images at a rate of five images per second. Figure 5 shows nine successive echo-planar NMR images spanning 1.6 s selected from 2400 images of water flowing in a loosely packed bed of spheres. Two large spheres and many small spheres are visible but their shapes are deformed by the difference in magnetic susceptibility between water and nylon in the 4.7 T field. In addition, sensitivity of the echo-planar method to velocity distribution can be seen clearly, for example, in frame (f). In this sequence of images the water is flowing down the tube fairly slowly after a rapid upward flow dislodged some small particles. One such small particle, which is in an unsteady position near the center of frames (a)–(c), is seen to fall in frames (d)–(e), resting in a more stable position in frames (f)–(i). As a bonus, we found that a sequence of these echo-planar images allows a visualization of the direction of water flow quite independently of any particle displacements. This was unexpected; we believed that intensity variation due to velocity heterogeneity would not contain any directional bias.

The final experiment used the Windows data system, with the 1.9 T magnet to make FLASH images in approximately 1.1 s per image. Figure 6 shows six successive NMR images of an air bubble rising in a soap solution. The field of view was 89 $\times$ 89 mm and the slice thickness was 6.5 mm. In image (d) there are some susceptibility artifacts seen as bright regions above and below the bubble. The velocity of the bubble decreases as it rises upward, it being 2.27 cm/s between frames (c) and (d), while it was 0.65 cm/s between frames (e) and (f). The real-time interactive imaging was useful in this experiment in order to adjust the flow rate to make an air bubble of appropriate size.

Factors Limiting the Image-Refresh Rate in Real-Time NMR Imaging

There are many factors limiting the image-refresh rate in real-time NMR imaging systems but they can be divided into two major categories: the imaging method and hardware. Although several fast imaging methods have been published (*8–13*), we compare only two methods, FLASH and EPI, for comparison. A detailed comparison is beyond the scope of this paper.

FLASH is a factor of 1.5 or more slower than EPI under the same hardware conditions (*14*) because it needs slice selection for every RF excitation and data cannot be collected during the inverted portion of the readout that is gradient-required before the gradient-echo formation. On the other hand, the magnetic susceptibility anisotropy effects are much worse for EPI as seen in Figs. 3 and 5.

There are various hardware factors which limit the real-time NMR imaging rate. Among them, eddy currents limit large gradient strengths and short switching times that are essential for rapid imaging pulse sequences such as EPI and FLASH. Another critical factor is the heating of gradient coils and/or power supplies. Indeed, in our experiments, the critical factor was heating of gradient coils in the first system and heating of power supplies in the second system. Although the heating may not present a problem in short-term experiments, it can be critical in long-term experiments where real-time NMR imaging has unique advantages over conventional imaging.

Our image-processing time, with the FLASH sequence, was about 30% of the image-repetition time in both systems and this is a significant fraction of the image-repetition time. In the future, faster personal computers and improvements in programming techniques to utilize multi-tasking will further reduce the image-processing time.

SUMMARY AND CONCLUSIONS

We have developed two real-time NMR imaging systems using high-speed personal computers. These systems have adequate processing speeds for many real-time im-

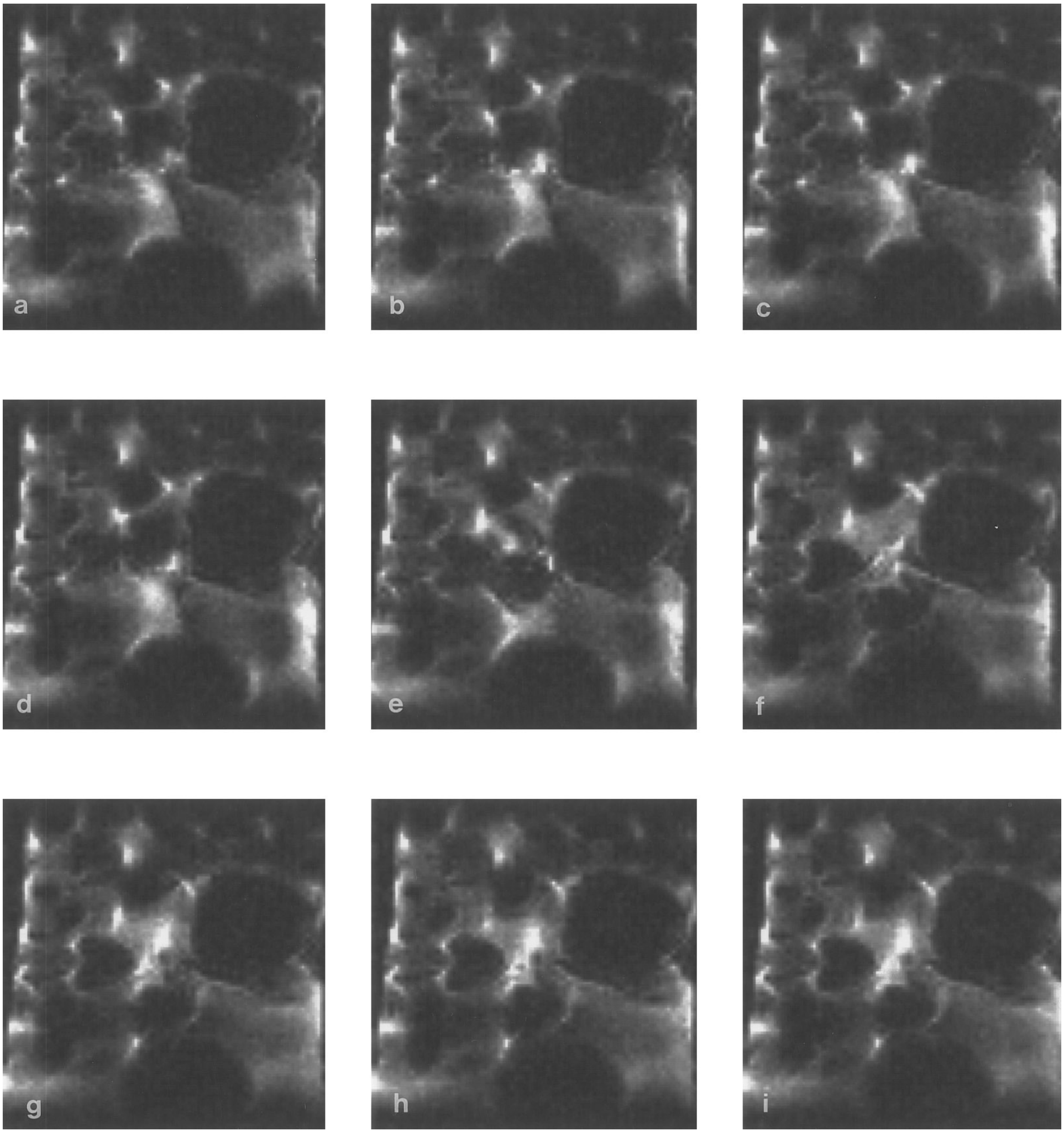

FIG. 5. Nine successive EPI images of water flowing in a loosely packed bed of spheres recorded with the DOS system. The field of view is 19.2 $\times$ 19.2 mm, the slice thickness is 4 mm, and the successive frames are 0.2 s apart. A small particle which was in an unstable position (near the middle of the image) falls in frames (d)–(f) after a rapid upward water flow just prior to this sequence of images dislodged it from the original position.

aging applications. The real-time system made with the Windows personal computer is easier to construct than any previously published; no special hardware components nor sophisticated software techniques are required. The performance of these real-time NMR imaging systems has been demonstrated using models of particles or bubble in fluids.

The essential advantage of the real-time NMR imaging systems over the conventional systems is the interactive operation which enables us to determine an optimal measurement condition, or an onset of some phenomenon in complex experimental systems, and perform some operation in response. This is especially true in optically opaque systems and for parameters that are hard to determine visually, e.g., onset of turbulence. Finally, we again point to the simplicity of the system, making it an ideal, independent add-on to existing medical and nonmedical NMR imaging apparatus. This general-purpose data-acquisition and real-time image-reconstruction system can also be useful in non-NMR applications.

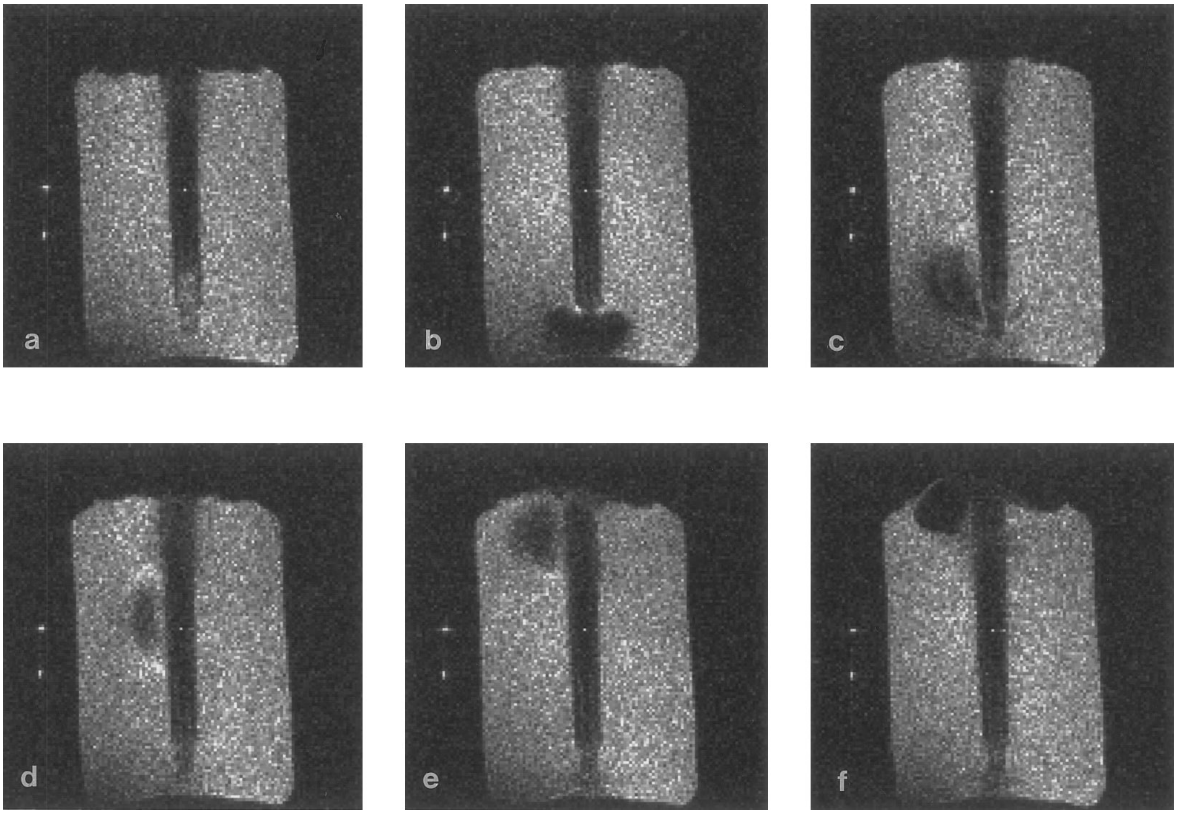

FIG. 6. Six successive FLASH images of an air bubble in a Dial soap solution recorded with the Windows system. The field of view is 89 × 89 mm, the slice thickness is 6.5 mm, and the successive frames are 1.12 s apart. In image (d) there are some susceptibility artifacts seen as bright regions above and below the bubble. The average velocity of the bubble between (c) and (d) was 2.27 cm/s and decreases as it goes higher.

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