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Imaging System Science Laboratory

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If we place a sample in a static magnetic field all the proton spins will precess about the field direction with the same angular frequency. When we apply an RF pulse which has the same frequency, Larmor frequency, the RF energy will be absorbed by all the protons and an FID signal would be produced from all the resonating protons. It is fairly easy to understand that the excitation of protons in a uniform magnetic field does not give any information about the spatial distribution of protons. An image on the otherhand is a multidimensional representation of an object in space. We realize that in order to make images, we must somehow, encode the spatial information into the FID signal.

A brilliant solution to this problem was provided by Lauterbur in 1973. He thought of a way in which the Larmor frequency from one point to another could be made different. Thus by tuning to the right frequency we can derive information from any spatial location within the object. This is similar to listening to a piano player without actually seeing him /her. If we know where each piano key is and have a good ear, by listening to the tune we would know where the piano player's hands are. This also is an example of spatially coding the piano frequencies. Lauterbur thought of adding a second magnetic field on top of the uniform static field. The property of the field is such that it increased as a function of

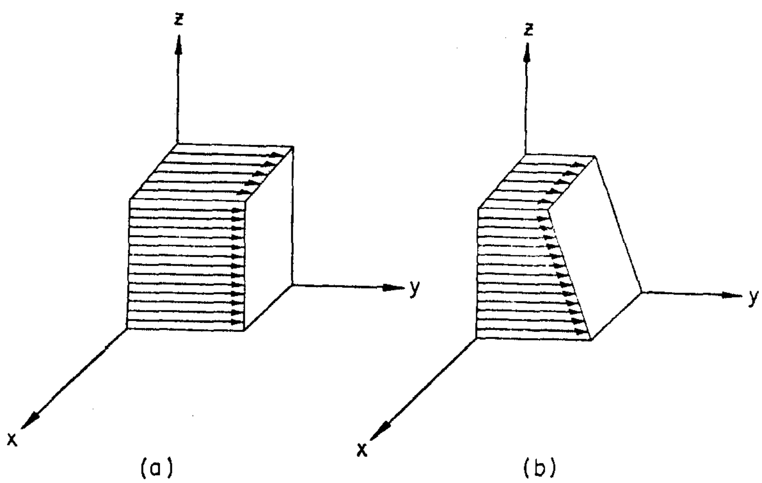

Fig. 1. (a) static field along z direction, (b) a linear gradient field in the same direction.

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distance linearly. Such a magnetic field is known as a linear gradient field. Earlier, we stated that the Larmor frequency is proportional to the magnitude of the magnetic field.

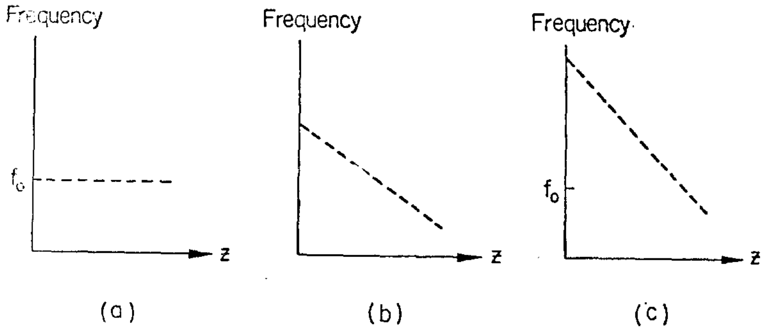

Fig. 2. (a) Constant Larmor frequency due to static field,
(b) Linearly varying additional frequency,
(c) Superposition of the two.

Thus, if the field varies linearly along, for example, the z coordinate of a Cartesian coor-

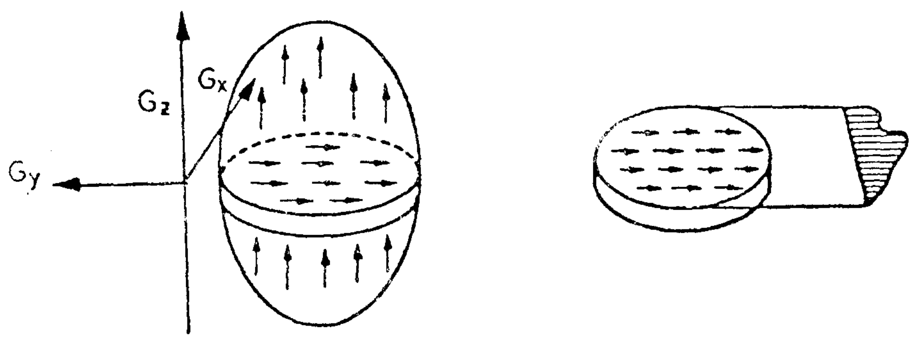

Fig. 3. Slice selection within an object.

dinate system, then the resonance frequency is obviously dependent on the location of the volume element of interest with respect to z.

In Figure 1(a), we see a static field of constant amplitude in z direction. In Figure 1(b), we observe a linearly decreasing gradient field in z direction. The Larmor frequency as a function of z direction is shown in Figure 2.

We immediately realize that by varying the RF frequency we can tune in any plane which is perpendicular to the z axis. This is shown in Figure 3.

By using a linearly varying gradient field, we simplified the problem from three dimensions to two dimensions. What is meant by this is that initially, without the gradient field, an RF pulse of Larmor frequency would have excited the whole volume. After the

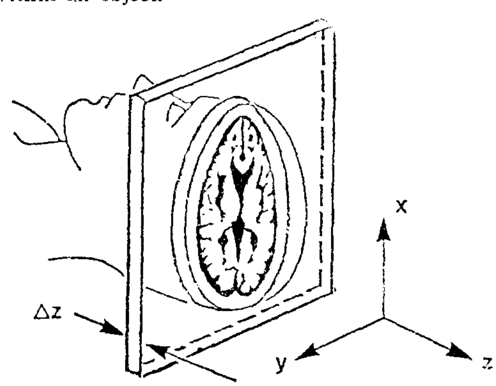

Fig. 4. By using a frequency selective RF pulse in the presence of a z gradient, excitation can be confined to a slice thickness z.

application of the z-gradient only a slice perpendicular to z-axis is excited. We can also vary the slice thickness by varying the RF pulse appropriately. The slice selection for a transaxial cut through the head is illustrated in the next figure.

Let us now demonstrate how we may image a phantom consisting of a teflon block having two water filled holes aligned with the z-axis but with different locations with respect to x (Fig. 5).

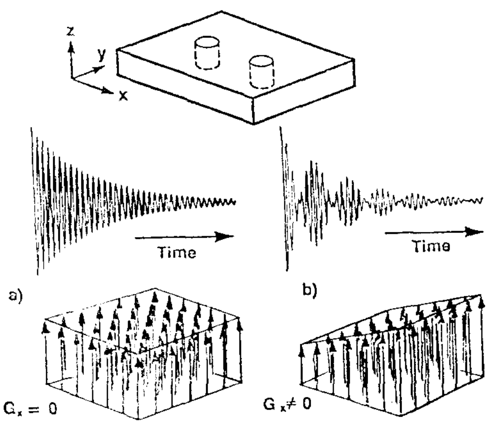

Fig. 5. Imaging a phantom with a gradient.

In the absence of the field gradient (Gx = Gy = Gz = O) both samples sense the same field; the FID therefore consists of a single frequency (Fig. 5a). In the presence of a gradient in the x direction, two samples sense different fields resulting in an FID signal consisting of two frequencies. In this case the excitation of both samples is achieved by sending an RF pulse which contains many different frequencies. Out of all these frequencies only two, corresponding to the Larmor frequencies at the sample sites, are absorbed. The combination of two frequencies made up the FID seen in Fig. 5b can be explained with the aid of following figure.

In Figure 6a, we have an FID with a certain frequency, in part b we have another FID with a higher frequency, Since the signals from both sites arrive simultaneously the overall FID is a sum of the two as shown in Figure 6c. We notice that the amplitude is cancelled at the center due to interference of the two FID's. In Figure 6, we did not include the overall attenuation due to relaxation effects which is shown in Figure 7 b:

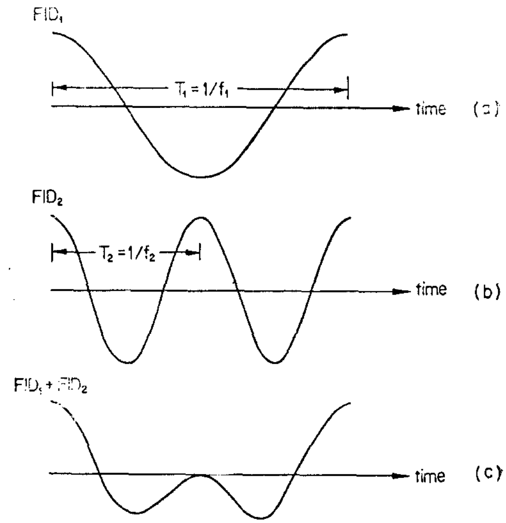

Fig. 6. Addition of two FID's with different frequencies.

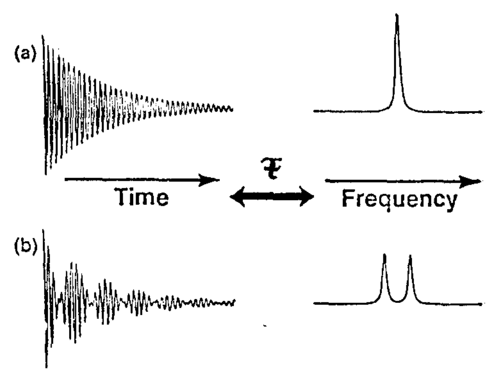

Fig. 7. FID signal and its Fourier domain analog for (a) a single frequency, (b) two different frequencies.

In reality, signals are collected from a multitude of spatial locations and the FID is a composite signal consisting of many different frequencies, not just the two which can be extracted by inspection, as in the phantom. To determine individual frequencies in such situations one resorts to a mathematical anaiysis, carried out in a computer. The process is called Fourier Transfrom. The FID represents the time evolution of transverse magnetization, the Fourier transfrom represents its frequency distribution. This not only allows extraction of the individual frequencies, but also their associated amplitudes, which are proportional to the spin density at the particulal spatial location. Figure 7 shows the free induction decay and its Fourier transform for the two signals in Figure 5.

In the first example of two water filled cylinders, we arbitrarily chose their location on the axis of the coordinate system. If we wish to determine their positions for the more general case where they are situated off-axis, we must determine both coordinates x and y for each sample. Let us assume the two cylinders to be within the xy plane as shown in Figure 8.

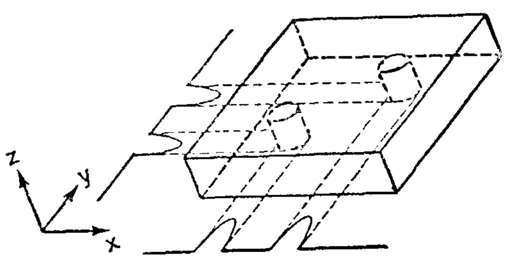

Fig. 8. Projection signals obtained from two water samples.

The first thing to do is to select the specific *z* plane where we are interested. This is done by applying a *z*-gradient field and sending an RF pulse which has a frequency corresponding to that plane. After that, a second gradient field in any arbitrarily direction within the xy plane is applied and the FID is measured. This is shown in the next figure,

The projection shown in Figure 9 is the summed magnetization in a direction which is perpendicular to the field gradient Gx′. It

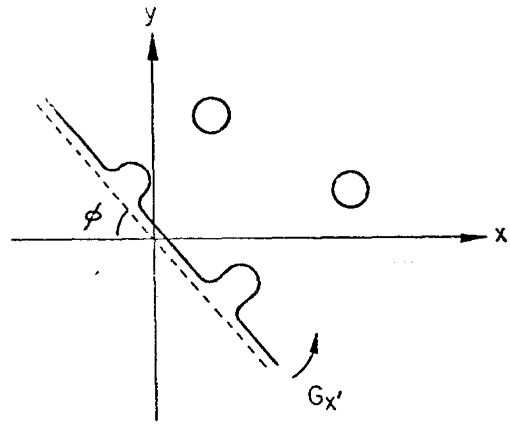

Fig. 9. Collection of projections in any arbitrary direction.

was obtained by Fourier transforming the FID signal measured along Gx′ similar to Fig. 7.

If we rotate the gradient field Gx′ with equal angular increments about *z* axis we would obtain a projection at each angle similar to computed tomography (CT). By using the mathematical reconstruction techniques beveloped in CT, one can then reconstruct the distribution of magnetization within the xy plane. The gray levels in each picture element would carry information about T_1,T_2

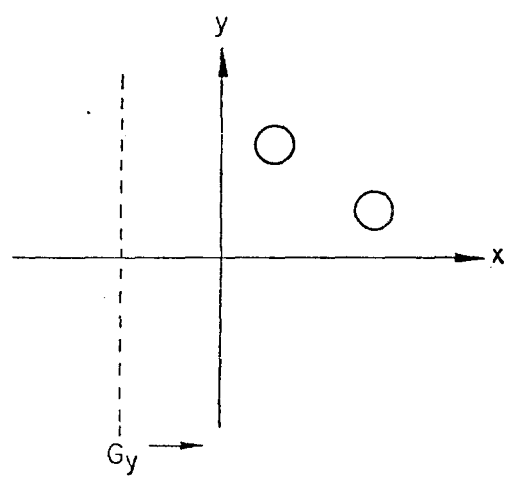

Fig. 10. Direct Fourier transform imaging.

or M_0 depending on what kind of excitation mechanism was used. We have just described projection-reconstruction technique of NMR imaging.

There is another technique called direct Fourier transform (DFF) method which does not utilize the reconstuction mathematics. In the DFT method the slice is again selected by using a z-gradient and a selectiee RF pulse. Here, instead of rotating the read out gradient Gx′ about the z axis we move it on square raster as shown in Figure 10.

At the end of moving the gradient along x direction, we obtain a two dimensional representation of the FID signal. By applying the Fourier transform technique in two dimensions, we get a two dimensional frequency distribution of the object. But since we know how frequencies vary spatially, we also know how the magnetic properties of the ocject being examined varies spatially.

There are many other variations of these techniques applicable to three dimensions but we will not go into these here.