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Visibility of Calcium on MR and CT: Can MR Show Calcium that CT Cannot?

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PURPOSE: To test the hypothesis that calcium can be visible on MR images without being visible on CT. **METHODS:** Five different calcium salts ranging in concentration from 0 to 0.45 g/mL were suspended in 2% agarose gel and studied using T2*-weighted MR, T1-weighted MR, and CT. MR signal intensity, CT attenuation, and image noise were measured. Relative visibility was determined from these measurements. **RESULTS:** CT was shown to be more than 10 times as sensitive as T2*-weighted MR or T1-weighted MR for the detection of calcium. **CONCLUSION:** MR cannot show calcium that is occult on CT.

Index terms: Magnetic resonance, comparative studies; Magnetic resonance, tissue characterization; Computed tomography, comparative studies; Brain, calcification

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Calcium can decrease or increase signal on magnetic resonance (MR) images; the direction of the signal change depends on the MR technique (1–5). It is generally believed that these MR signal changes can be seen only at calcium concentrations higher than that required be visible on computed tomography (CT). The purpose of this study was to test the hypothesis that calcium can cause a visible decrease in signal on T2*-weighted gradient-echo MR, or increase in signal on T1-weighted spin-echo MR, without being visible on CT.

Methods

MR signal intensity and CT attenuation were measured in a series of test tubes filled with varying amounts of particulate calcium salts. The salts were suspended in 2% agarose gel to eliminate precipitation. Two different calcium salts were studied, calcium hydroxyapatite and calcium carbonate. To allow for potential physicochemical variability between samples, four types of calcium hydroxyapatite (BDH Chemicals product 44257, BDH Chemicals product 44225, Schweizerhall product 51-7100-20, and Schweizerhall product 51-7100-10) and one type of calcium carbonate (Fluka product 21060) were tested. Our previous work with these products demonstrated differences in T1 relaxivity, T2 relaxivity, and surface area (6). In total, five types of samples were prepared. Each type was studied at calcium salt concentrations ranging from 0 to 0.45 g/mL.

MR signal was measured with an optimized gradient-echo T2*-weighted 100/25/4 (repetition time/echo time/excitations), 30° flip angle, and a spin-echo T1-weighted 400/20/1 technique on a 1.5-T whole-body scanner (6, 7). Both the T2*-weighted and T1-weighted images were obtained at a 256 × 256 matrix with a 24-cm field of view and a 5-mm section thickness. The T2*-weighted images were obtained at 4 excitations and the T1-weighted method at 1 excitation. This made the acquisition times for the two methods equivalent. CT attenuation was measured on a conventional CT scanner on the same samples with a 512 × 512 matrix, 11-cm field of view, and 5-mm section thickness. Signal (attenuation) from each of the studies was plotted as a function of calcium concentration (Fig 1).

The noise for each sample was measured as the random variation in the image background. This was then converted to represent the standard deviation of the signal within the region of interest (8). Relative visibility of calcium with each technique was then calculated (see Results for explanation).

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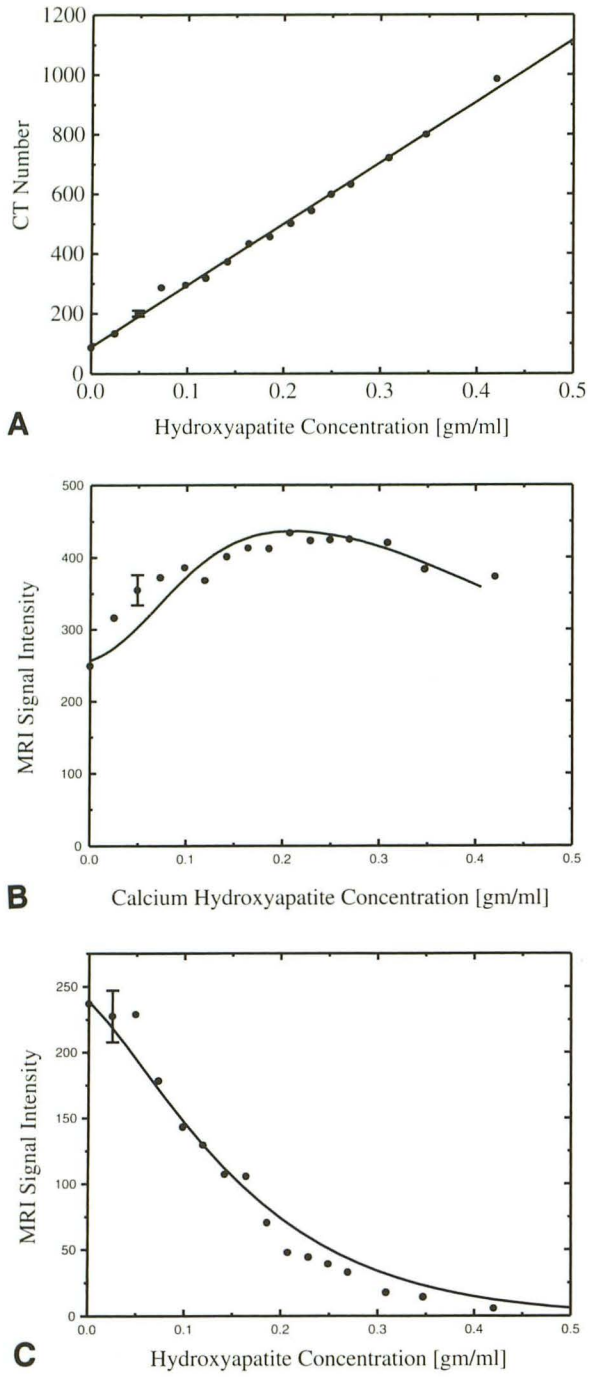

Fig. 1. Signal intensity versus concentration of calcium hydroxyapatite for *A*, CT, *B*, T1-weighted spin-echo MR (400/20), and *C*, T2*-weighted gradient-echo MR (100/25, 30° flip angle). Data points correspond to experimental measurements. The representative *error bar* in each figure corresponds to the standard deviation throughout the sample and to the error observed in repeat measurements. The *solid lines* are theoretically predicted behavior.

A, A linear regression based on the x-ray attenuation of calcium hydroxyapatite.

B, Enhanced signal intensity caused by surface relaxation (6).

C, decreased signal intensity based on susceptibility effects and small tip angle section profiles (7). The slopes of the curves at [Ca] ≈ 0 are taken from the theoretical curves.

Results

Relationship Between Signal and Calcium Concentration

The relationships between image signal and calcium concentration for one of the samples (calcium hydroxyapatite, BDH Chemicals 44257) for each of the three techniques are shown in Figure 1. The solid lines in the MR figures represent calculations using measured T1, T2, and T2* of the calcium samples and represent simple linear regression for the CT. The MR data illustrated is for the calcium samples having the greatest effect on MR signal intensity (calcium hydroxyapatite, BDH Chemicals 44257). The CT data varied by less than ±4%; therefore, the illustrated CT data essentially can be taken to represent any of the samples.

On CT there was a direct linear relationship between signal and calcium concentration. On T2*-weighted MR, signal decreased with increased calcium concentration, an effect known to be principally attributable to suspectibility-induced dephasing of the MR signal by the calcium. On T1-weighted MR, signal increased initially with increased calcium concentration because of T1 shortening in bulk water caused by the surface of calcium salts (6), then at higher calcium concentrations signal decreased because of the effect of progressively lower proton density and T2 shortening.

Image Noise on T2-Weighted MR, T1-Weighted MR and CT*

The standard errors of the mean arising from noise measured in a 5-mm region of interest in a 5-mm-thick section for each of the three techniques were: T2*-weighted MR, 4.26; T1-weighted MR, 1.98; CT, 0.752.

Visibility of Calcified Objects

For an object of constant size, the confidence with which the object can be seen on any image is related to the difference in signal between the object and the background signal (image contrast), the random variation in the background signal caused by noise over the size of the object, and a confidence limit determined by a normal distribution. For 95% confidence in identification, the image contrast must exceed the noise by a

factor of 1.65 or greater, where 1.65 is the 95% limit for a one-tailed normal distribution.

The minimum calcium concentration ([Ca]) that must be present in an object for 95% confidence in detection is thus determined by the relationship:

$$[Ca]_{minimum} \geq (1.65) \times (noise)/(dS/(d[Ca]),$$

where dS/(d[Ca] is the slope of the signal versus calcium concentration curve (see Fig 1).

The term dS/(d[Ca]) for different calcium samples varied by a factor of 10 for the T1-weighted MR and by a factor of four for the T2*-weighted MR. However, because the hypothesis being tested was whether either of the MR techniques (T2*-weighted or T1-weighted) could show calcium when CT could not, only that sample (calcium hydroxyapatite, BDH Chemicals #44257) in which the MR effect was strongest is analyzed further.

For those samples in which the MR effects were strongest, the slopes of the curves of signal versus calcium concentration for CT and MR show that in the area in which calcium concentration was approximately zero, dS/d[Ca] was: 2050 units of signal increase per gram per milliliter of calcium for CT; 600 units of signal increase per gram per milliliter of calcium for T1-weighted MR; and 975 units of signal decrease per gram per milliliter of calcium for T2*-weighted MR. Substitution of these measured values in the equation above leads to the conclusion that the minimum detectable calcium concentration for each of these methods at the 95% confidence limit is: 0.0006 g/ml for CT, 0.005 g/ml for T1-weighted MR, and 0.007 g/ml for T2*-weighted MR.

For samples with lesser MR effects, calcium concentrations as high as 0.05 g/ml were required for visualization on the T1-weighted technique, and as high as 0.03 g/ml for the T2*-weighted technique. Changes in the size of the object considered or in the confidence limit would cause a proportional change in each of the above concentrations, but the relative differences between the techniques would remain the same.

Discussion

We have studied several different calcium salts with T1-weighted MR, T2*-weighted MR, and CT, and we have demonstrated that CT was much more sensitive than either MR technique for the detection of calcium. We found that CT was more than 10 times as sensitive as T1-weighted MR for the calcium sample with greatest effect on T1 relaxation, and more than 10 times as sensitive as T2*-weighted MR for the calcium sample with greatest effect on T2* relaxation. CT was even more sensitive for the other calcium samples. Thus we conclude that MR cannot detect calcium that is occult on CT.

Our experiment is not definitive proof that there are not other types or forms of calcium that have greater effects on MR signal. The conclusion that CT is more sensitive than MR can only be applied with certainty to the samples and techniques tested in this experiment. However, it is unlikely that the MR effects of other types of calcium salts would be greater by 10- to 50-fold, which would be the amount required to reverse the sensitivity scale.

It also could be argued that alternative MR or CT techniques could change the relative sensitivity of MR and CT for calcium detection. This is also unlikely. The T2*-weighted technique we used had been optimized for the detection of susceptibility-induced signal loss (7); the high signal intensity occasionally observed on T1-weighted images is not dependent on minor changes in MR timing parameters. Furthermore, the methods we used are those commonly used in clinical practice. Thus at a minimum our results represent the clinical situation.

Finally, we conclude that in situations in which calcium is responsible for high signal intensity on T1-weighted images or for low signal intensity on T2*-weighted images, the calcium should always be visible on CT as an area of high attenuation. Conversely, unless visible on CT as a bright focus, an area of reduced signal on T2*-weighted MR or high signal on T1-weighted MR cannot be explained on the basis of calcium alone. There must be some other material present, alone or in combination with calcium, causing the signal change. We speculate that the hypointensity in lesions visible as hypointense on T2*-weighted MR but not visible on CT is caused by iron, and further speculate that hyperintense areas on T1-weighted MR not visible on CT are caused by any one of a number of paramagnetic trace metals, or possibly macromolecules with T1-shortening effects.

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