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An Index System for Comparative Parameter Weighting in MR Imaging

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Abstract: An analytic method for comparative parameter weighting in magnetic resonance (MR) imaging has been developed using the concept of "fractional sensitivity." This new approach results in easily calculated indexes for T1, T2, and hydrogen weighting. This index system enables quantitative comparisons to be made between MR studies that have been performed at various field strengths, using different pulse sequences and pulse timing intervals.
Index Terms: Pulse sequence—Magnetic resonance imaging, comparative studies—Magnetic resonance imaging, physics and instrumentation.

The terms "T1-weighted image" and "T2-weighted image" have flourished for several years in the magnetic resonance (MR) radiology literature. Despite the liberal usage of these terms, there is no general agreement as to their definitions. Furthermore, it is arguable how to quantitate the degree of T1, T2, or hydrogen density (N) weighting a given pulse sequence actually possesses.

These points are easily illustrated by reviewing the pulse sequences used in a recent issue of *Radiology* (Table 1). In the four clinical MR articles reviewed, there were 15 different T1-weighted pulse sequences and 24 different T2-weighted pulse sequences used to generate images and scientific data (1–4). This large array of potential pulse sequences performed at different magnetic field strengths makes comparison of studies difficult.

The following questions might potentially arise: Is a spin echo (SE) 2,500/60 image of the brain performed at 1.5 T more or less T2 weighted than an SE 1,500/120 image performed at 0.5 T? Is an SE 500/30 image performed at 0.5 T more or less T1 weighted than an SE 800/20 image performed at 1.5 T? Furthermore, just how much T2 and N weighting do these alleged T1-weighted images actually possess?

In an attempt to answer these questions, some sort of quantitative approach seems necessary. To accomplish this, the idea of MR parameter "fractional sensitivity" will be developed. Using the fractional sensitivity concept, easily calculable T1-, T2-, and N-weighting indexes can be derived. Such indexes will allow quantitative comparisons to be made between various MR studies that have been performed at different field strengths, using different pulse sequences and timing intervals. This formulation will initially be made for the SE pulse sequence at 0.35 T, and later expanded to include inversion recovery (IR) techniques and modifications for other field strengths.

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FRACTIONAL SENSITIVITY

A number of authors have approximated solutions to the classic Bloch equations for tissue magnetization to produce a formula for calculating signal intensity I in an MR image (5,6):

$$I = KN\,(1 - e^{-TR/T1})e^{-TE/T2} \qquad (1)$$

where

K = velocity and scaling term
N = hydrogen (spin) density
TR = repetition time
TE = echo time
T1 = spin-lattice relaxation time
T2 = spin-spin relaxation time

This formula assumes perfectly homogeneous 90° and 180° pulses as well as the condition that T1 and TR are much greater than TE.

The partial derivatives of I with respect to T1, T2, and N have traditionally been used as measures

TABLE 1. *Large number of pulse sequences used in MR papers from a single issue of* Radiology *(November 1986)*

T1-weighted images	T2-weighted images
SE 350/22 (1.5 T)	SE 1,000/56 (0.35 T)
SE 350/32 (0.5 T)	SE 1,500/60,120 (0.5 T)
SE 400/15 (1.4 T)	SE 2,000/30,60 (1.5 T)
SE 400/28 (0.5 T)	SE 2,000/40,80 (1.5 T)
SE 500/30 (0.5 T)	SE 2,000/32,64,96,128 (0.5 T)
SE 500/35 (0.35 T)	SE 2,000/28 (0.35 T)
SE 500/40 (0.35 T)	SE 2,000/60 (0.5 T)
SE 530/30 (0.35 T)	SE 2,000/90 (0.5 T)
SE 533/33 (0.5 T)	SE 2,000/80 (0.35 T)
SE 600/20 (1.5 T)	SE 2,000/100 (1.4 T)
SE 600/25 (1.5 T)	SE 2,120/120 (0.35 T)
SE 600/30 (0.5 T)	SE 2,500/30,60 (1.5 T)
SE 800/20 (1.5 T)	SE 2,500/40,80 (1.5 T)
SE 800/25 (1.5 T)	SE 2,600/99 (0.5 T)
IR 1,400/400 (0.5 T)	SE 3,500/90 (1.5 T)
	SE 3,500/120 (1.5 T)

of parameter sensitivity (7). These are obtained by straightforward differentiation:

$$\partial I/\partial \mathrm{T1} = -(1/\mathrm{T1})^2 \cdot \mathrm{N} \cdot K \cdot \mathrm{TR} \cdot e^{-\mathrm{TR/T1}} \cdot e^{-\mathrm{TE/T2}} \quad (2)$$

$$\partial I/\partial \mathrm{T2} = (1/\mathrm{T2})^2 \cdot \mathrm{N} \cdot K \cdot \mathrm{TE} \cdot (1 - e^{-\mathrm{TR/T1}}) \cdot e^{-\mathrm{TE/T2}} \quad (3)$$

$$\partial I/\partial \mathrm{N} = K \cdot (1 - e^{-\mathrm{TR/T1}}) \cdot e^{-\mathrm{TE/T2}} \quad (4)$$

Unfortunately, there are several problems with using these partial derivatives as absolute measures of MR signal sensitivity and parameter weighting. First of all, they are complicated multivariate functions of little intuitive value. Complex graphs are required for their display.

A more serious problem with using these derivatives alone is that maximizing a given derivative does not ensure that the resultant MR pulse sequence will be maximally weighted by that variable. For example, suppose that for a given tissue (with fixed T1, T2, and N values), TR and TE are chosen so that $\partial I/\partial$T1 is very large. Making $\partial I/\partial$T1 large implies that the MR signal intensity I will be very sensitive to changes in tissue T1. However, this same choice of TR and TE may also happen to cause $\partial I/\partial$T2 to be very large as well. With $\partial I/\partial$T2 large, the pulse sequence will have high sensitivity to changes in T2 as well as T1. As a consequence, the pulse sequence will not be either T1 or T2 weighted, but rather balanced. Clearly, then, a measure of parameter weighting must somehow include variations due to $\partial I/\partial$T1, $\partial I/\partial$T2, and $\partial I/\partial$N to be meaningful.

The concept of fractional sensitivity will be used to measure the following quantity:

$$\frac{\%\text{ change in MR signal } (I)}{\%\text{ change in tissue parameter (T1, T2, or N)}} \quad (5)$$

The idea is as follows: Suppose one records a baseline SE signal (I) from a tissue with intrinsic parameters T1, T2, and N. Now let pathology affect the tissue so that T2 is increased from baseline by 10%. If the MR signal intensity increases 5% above its base value, the fractional sensitivity of this sequence to T2 is ~5%/10% or 0.5. Similar measures for T1 and N fractional sensitivities may be defined.

More formally, parameter fractional sensitivity can be defined in terms of the total differential of I:

$$dI = \frac{\partial I}{\partial \mathrm{T1}} d\mathrm{T1} + \frac{\partial I}{\partial \mathrm{T2}} d\mathrm{T2} + \frac{\partial I}{\partial \mathrm{N}} d\mathrm{N} \quad (6)$$

By straightforward algebraic manipulations of identity 6 with formulas 2–4, we obtain

$$\frac{dI}{I} = S_{\mathrm{T1}} \frac{d\mathrm{T1}}{\mathrm{T1}} + S_{\mathrm{T2}} \frac{d\mathrm{T2}}{\mathrm{T2}} + S_{\mathrm{N}} \frac{d\mathrm{N}}{\mathrm{N}} \quad (7)$$

where

$$S_{\mathrm{T1}} = \frac{\mathrm{TR/T1}}{1 - e^{\mathrm{TR/T1}}} \quad (8)$$

$$S_{\mathrm{T2}} = \mathrm{TE/T2} \quad (9)$$

$$S_{\mathrm{N}} = 1 \quad (10)$$

are called "fractional sensitivities" of I with respect to T1, T2, and N.

It can be seen that these fractional sensitivities are limiting approximations of the ratio in Eq. 5, since dI/I can be considered a percentage change in I while dT1/T1, dT2/T2, and dN/N can be regarded as percentage changes in tissue parameters T1, T2, and N. Note also that each fractional sensitivity expression is independent of the other tissue parameters (e.g., S_{T1} is independent of both N and T2). Furthermore, Eqs. 8–10 do not contain the bothersome scaling factor K nor the difficult-to-measure quantity N.

MR PARAMETER WEIGHTING INDEXES

The concept of fractional sensitivity may be utilized to define weighting indexes for each tissue parameter:

$$\mathrm{T1WI} = \text{T1-weighting index} = \frac{S_{\mathrm{T1}}}{|S_{\mathrm{T1}}| + |S_{\mathrm{T2}}| + |S_{\mathrm{N}}|} \quad (11)$$

$$\mathrm{T2WI} = \text{T2-weighting index} = \frac{S_{\mathrm{T2}}}{|S_{\mathrm{T1}}| + |S_{\mathrm{T2}}| + |S_{\mathrm{N}}|} \quad (12)$$

$$\mathrm{NWI} = \text{N-weighting index} = \frac{S_{\mathrm{N}}}{|S_{\mathrm{T1}}| + |S_{\mathrm{T2}}| + |S_{\mathrm{N}}|} \quad (13)$$

These weighting indexes have been designed so that they have two properties: (a) Each is a fraction between −1 and 1, and (b) |T1WI| + |T2WI| + |NWI| = 1. It will thus be possible to say, for example, that a given SE pulse sequence, when applied to the brain, is 10% T1 weighted, 60% T2 weighted, and 30% N weighted. The weighting indexes represent scaled and normalized fractional sensitivities.

What does it mean to say that a pulse sequence is 10% T1 weighted, 60% T2 weighted, and 30% N weighted? It means that the respective fractional sensitivities $S_{T1}:S_{T2}:S_N$ are in size related by the ratio 1:6:3. A χ% change in T2 would have six times as large an effect on signal intensity as a χ% change in T1. Similarly, it would have twice as large an effect on signal intensity as a χ% change in N. While admittedly arbitrary, this formulation provides much needed insight into otherwise complicated equations and gives a basis for comparing the weighting of different pulse sequences quantitatively.

APPLICATION OF WEIGHTING INDEXES TO CRANIAL MR IMAGING AT 0.35 T

Each weighting index is seen to be a function of four variables: T1, T2, TR, and TE. Clearly, the weighting of an MR pulse sequence will depend upon the imaged tissue of interest; a given pulse sequence applied to brain would reflect different T1 and T2 sensitivities than when applied to liver. To develop a usable set of weighting indexes, therefore, it will be necessary to specify mean or central values of T1 and T2 for the tissue of interest. Pathological changes in that tissue will then be reflected by fractional changes in these beaseline T1 and T2 values.

As an example, let us calculate weighting indexes for the brain at 0.35 T. In the brain most lesions are seen by virtue of their contrast with parenchyma (gray or white matter). At 0.35 T a reasonable average or central T1 value for brain parenchyma would be ~500 ms (8,9). It should be noted that the central T1 value varies with field strength, and the MR weighting indexes will be changed as field strength is increased (see below). Selecting an average or central value for T2 is more difficult, since different investigators measure this multicomponent relaxation time in various ways (8,9). Using the data of Kjos et al. (9) as well as our own measurements, we will choose 60 ms as an average or central value for brain T2. While T1 is field dependent, the T2 relaxation time is relatively independent of field strength (8).

Using central values (T1 = 500 ms and T2 = 60 ms) for brain parenchyma at 0.35 T, it is an easy matter to calculate weighting indexes for T1, T2, and N using Eqs. 8–13. Parameter weighting indexes for a variety of commonly used MR pulse sequences have been computed and are displayed in Table 2. These indexes, while admittedly arbitrary, do give certain insights into the relative parameter weighting of various MR imaging sequences that may not be immediately obvious to many diagnosticians.

As is well known, progressively greater T1 weighting is obtained by using progressively shorter TR and TE values. This is certainly no surprise. What is more enlightening, however, is to see how much T2 and N dependence these short SE sequences actually possess. For example, the SE 500/30 sequence, commonly called "T1 weighted," has T1WI = −24%, T2WI = 24%, and NWI = 48%. If anything, this sequence should be considered more sensitive to changes in spin density than to either T1 or T2. Furthermore, the MR signal obtained from normal brain parenchyma using this technique is equally T1 and T2 weighted.

The data in Table 2 also support a second well accepted doctrine in SE imaging: Progressive T2 weighting is obtained by lengthening TR or TE. What is a little surprising is the trade-off between TR and TE that can be made while still maintaining equivalent T2 weighting of the MR image. For example, it can be seen that when applied to tissues similar to brain, an SE 500/120 sequence is actually more T2 weighted than an SE 3,000/60 sequence. Of course, if tissue T1 were very long, such as in cerebrospinal fluid, the SE 500/120 image would have more T1 weighting. Nevertheless, its T2WI would still be greater than that of the SE 3,000/60 sequence.

The parameter weighting indexes also reflect the well established principle that an N-weighted image is produced by making TR long and TE short. The

TABLE 2. *MR parameter weighting indexes for SE brain imaging at 0.35 T*

Pulse sequence		T1WI	T2WI	NWI
TR (ms)	TE (ms)	(%)	(%)	(%)
250	30	−34	22	44
	60	−28	36	36
	120	−20	53	26
500	30	−28	24	48
	60	−22	39	39
	120	−16	56	28
1,000	30	−17	28	55
	60	−13	43	43
	120	−9	60	30
2,000	30	−5	32	63
	60	−4	48	48
	120	−2	65	32
3,000	30	−1	33	66
	60	−1	49	50
	120	0	66	34

critical feature seems to be making TE short. Nevertheless, even with TE as short as 15 ms, the NWI cannot be pushed much above 80%.

MODIFICATION OF INDEXES BASED ON FIELD STRENGTH

The parameter weighting indexes presented in Table 2 were based upon the central T1 value for brain at 0.35 T, taken to be ~500 ms. While T2 is relatively constant with field strength, T1 changes significantly over the range of fields commonly used in MR imaging (0.15–2.0 T). While both exponential and linear models can be used to fit the data, the most accurate model seems to be $T1 = AB_0^C$, where A is a proportionality constant, B_0 is the magnetic field strength in Teslas, and C is an exponential constant, which for most tissues is ~⅓ (8,10). Thus, when field strength is increased from 0.35 to 1.5 T, T1 values should increase by a factor of $(1.5/0.35)^{⅓} = 1.6$. If we have chosen T1 = 500 ms to be the representative relaxation time for brain at 0.35 T, at 1.5 T we should choose T1 = 500 × 1.6 = 800 ms, which is in agreement with published measurements of T1 at high fields (8).

Table 3 shows how changing field strength affects the MR parameter weighting indexes for the SE 500/30 and SE 2,000/120 pulse sequences. Note that when going from low to high fields, the relative T1 weighting of a given pulse sequence increases while T2 and N weighting decrease slightly.

WEIGHTING INDEXES FOR IR PULSE SEQUENCES

The concepts of fractional sensitivity and parameter weighting may be easily applied to the IR pulse sequence. As implemented on most commercial scanners today, both phase sensitive detection as well as SE signal generation are used (11). Accordingly, the equation for MR signal intensity may be written

$$I = K_{IR}N\,(1 - 2e^{-TI/T1} + e^{-TR/T1})e^{-TE/T2} \quad (14)$$

where I, N, T1, T2, and TE are defined as for Eq. 1, TI is the inversion time, and K_{IR} is a factor for velocity and scaling.

Partial derivatives of I with respect to T1, T2, and N may again be taken, and fractional sensitivities calculated as in Eqs. 7–10. The results are similar to, although a little more complicated than, the SE sequence.

$$S_{T1} = \frac{-2\,(TI/T1)\,e^{-TI/T1} + (TR/T1)\,e^{-TR/T1}}{1 - 2e^{-TI/T1} + e^{-TR/T1}} \quad (15)$$

$$S_{T2} = TE/T2 \quad (16)$$

$$S_N = 1 \quad (17)$$

The T1-, T2-, and N-weighting indexes may be defined as in formulas 11–13 using these IR fractional sensitivities. Again using brain parenchyma at 0.35 T as a baseline tissue, weighting indexes may be easily calculated for each TR, TI, and TE. Weighting indexes for several popular IR sequences are presented in Table 4. As can be seen from the table, short TI IR sequences (IR 1,000/100/30) are mostly T2 and N weighted. Medium TI sequences (such as IR 1,000/250/30 and IR 1,500/500/30) are highly T1 weighted, more so than even the best SE sequence in Table 2. As is well appreciated, these medium T1 sequences give excellent T1 contrast clinically.

DISCUSSION

The terms "T1 weighted" and "T2 weighted" are among the most widely and inconsistently used expressions in MR imaging. Because of the confusion and ambiguity surrounding them, these terms were purposely omitted from the recent revision of the "Glossary of MR Terms" by the American College of Radiology (12).

In 1983 Edelstein et al. (13) presented an early mathematical attempt to quantify MR parameter sensitivity. This approach, limited to T1 discrimination sensitivity, was applied to partial saturation and IR techniques. The ideas expressed therein, especially the use of contrast-to-noise (CNR) and figure-of-merit ratios, were influential in shaping

TABLE 3. *Variation of weighting indexes with field strength*

	SE 500/30		SE 2,000/120	
	At 0.35 T	At 1.5 T	At 0.35 T	At 1.5 T
T1WI	−24	−33	−2	−7
T2WI	24	22	65	62
NWI	48	45	32	31
Central T1 value used	500	800	500	800

TABLE 4. *Weighting indexes for representative IR pulse sequences applied to brain at 0.35 T*

IR sequence					
TR	TI	TE	T1WI	T2WI	NWI
1,000	100	30	7	31	62
1,000	250	30	73	9	18
1,500	500	30	−56	15	29
2,500	500	30	−63	12	24
3,000	1,000	30	−33	22	45

future analyses of parameter sensitivity of MR pulse sequences, typified by the recent work of Young et al. (14).

To approach MR parameter weighting from a CNR perspective is valid and useful. However, several additional assumptions need to be made (14). First, noise statistics must be presumed (usually white noise) and the slice edge characteristics must be considered to be perfectly sharp. Second, the noise level is assumed to be proportional to the bandwidth of data acquisition and inversely proportional to the acquisition time for a fixed number of samples. Furthermore, baseline values of N, T1, and T2 must be assumed for two different tissues, usually the normal organ and its adjacent pathological focus. The CNR method is therefore a *two tissue* approach, defining parameter weighting and sensitivity in terms of tissue pairs with known characteristics (N, T1, and T2).

By contrast, the method developed in the present article is a *one tissue* approach, defining parameter weighting and sensitivity in terms of variations in the intrinsic properties of a *single* background tissue. Early or minimal pathology within an organ (such as a focus of edema, hemorrhage, or tumor) becomes manifest on MR imaging because of a small but definite deviation of N, T1, or T2 from baseline levels. The ability of an MR pulse sequence to be sensitive to such small changes in tissue N, T1, or T2 forms the basis for defining parameter weighting in the new index system method presented here. While not denying the utility of the two tissue (CNR) method for parameter weighting, the one-tissue approach provides several advantages, including ease of calculation and a model for the imaging of early and minimal disease.

CONCLUSIONS

1. Up to now, the terms "parameter weighting" and "parameter sensitivity" have been loosely and inconsistently used in the MR literature.

2. The concept of parameter fractional sensitivity has been developed, which is an estimate of (% change in MR signal) ÷ (% change in tissue parameter T1, T2, or N).

3. A T1-weighting index (T1WI), T2-weighting index (T2WI), and spin density–weighting index (NWI) have been defined that are directly related to fractional sensitivities. The weighting indexes are all scaled such that they are numbers between −1 and 1, and normalized so that their sum is 1.

4. These fractional sensitivities and weighting indexes provide a basis for comparing MR studies that have been performed at various field strengths, using different pulse sequences and pulse timing intervals.

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