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Contrast-enhanced abdominal echo planar imaging: Dynamic signal-intensity changes following intravenous injection of gadolinium-DOTA

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Objectives: After I.V. administration of gadolinium-DOTA, the early contrast enhancement pattern and related signal-intensity (SI) changes in normal abdominal organs (kidney, spleen, liver) are evaluated over the first 4 min by using ultrafast spin-echo echo planar imaging (SE-EPI).

Methods: On a 1.5-T magnetic resonance unit ultrafast EPI of the upper abdomen was performed in 12 patients in order to show the contrast enhancement pattern and related measurable SI changes on T_1- and T_2-weighted (w) images over the first 4 min after I.V. bolus injection of 0.1 mmol kg^{-1} gadolinium (Gd)-DOTA in the spleen, liver, renal cortex, and renal medulla. A TR/TE of 500/44 or 45 ms in T_1-w SE-EPI and a TR/TE of 2000/80 or 100 ms in T_2-w SE-EPI were used.

Results: Typical time-dependent SI changes were noticed on T_1-w images: Subsequent to a SI increase in the renal cortex (starting 7 s after the I.V. injection of Gd-DOTA) SI increased first in the outer renal medulla (6 s later) and then in the inner renal medulla (21 s later). A SI increase was observed in the spleen (starting after 15 s) and in the liver (starting 7 s later). On T_2-w images, a SI decrease in the renal cortex (starting after 14 s) was followed by migration of a "dark band" from the outer (after 46 s) to the inner medulla (after 70 s). Only minimal changes were noticed in the spleen and liver.

Conclusions: Ultrafast SE-EPI following I.V. bolus injection of Gd-DOTA enables the observation of the very early contrast agent kinetics in various abdominal organs. The associated SI changes on T_1- and T_2- SE EPI are related to organ perfusion and contrast agent tissue concentration and biodistribution.

Keywords: echo planar imaging, abdominal organs, gadolinium-DOTA, contrast enhancement dynamics.

INTRODUCTION

Echo planar imaging (EPI) is an ultrafast magnetic resonance (MR) imaging technique with acquisition times as short as 40 ms per single slice, thus providing the possibility of real-time imaging.

A dynamic signal must be sampled at least twice as fast as the information is changing. For studies of tissue perfusion of the liver, spleen, and kidneys, the imaging sequence must have a temporal resolution of 0.3–3 images per second [2]. EPI provides even a faster image acquisition and the immediate biodistribution of a paramagnetic extracellular agent after intravenous administration can be evaluated. This allows the analysis of the early enhancement pattern and perfusion of both normal organs and pathologic lesions [1, 2].

The purpose of this study was to evaluate the early contrast enhancement and related signal-intensity (SI) changes in normal abdominal organs (kidney, spleen, and liver) after intravenous administration of a standard dosage of gadolinium (Gd)-DOTA by using

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ultrafast T_1- and T_2-weighted (w) spin echo (SE)-EPI with standard imaging parameters.

MATERIAL AND METHODS

All MR images were obtained on a superconducting 1.5-T MR unit (General Electric GE, Signa Advantage, Milwaukee, USA) equipped with additional hardware and software. The hardware additions included a fast receiver that allowed sampling at a maximum rate of 1 MHz and a nonresonant EPI-capable whole-body gradient coil with a fast ramping gradient amplifier in the x axis providing a rise time of less than 100 μs. On the y axis an additional standard amplifier allowed a rise time of 250 μs. The additional software installed in our standard clinical GE-Signa unit provided a high-speed data acquisition, and pulse programs such as SE-EPI, gradient-echo (GRE)-EPI, and interleaved EPI.

Contrast-enhanced dynamic SE-EPI was performed in 12 patients (7 women and 5 men, mean age 55 years) who were submitted to a MR examination of the pelvis or of the musculosceletal system with clinically suspected pathology in these areas but without known pathologies of the upper abdominal organs. The injection of gadolinium-DOTA in our patients was always necessary in order to get a correct examination of the suspected pathology in every patient. In all patients, just one additional EPI-SE series was performed for scientific reasons; all other sequences were obtained for medical reasons. Before the beginning of the examinations, the patients were carefully informed about the potential risks of our study by the radiologist, present in the MR unit, and written consent was routinely obtained by every patient.

A single-shot EPI sequence was obtained using a TR/TE of 500/44 or 45 ms in T_1-w (six patients) and of 2000/80 or 100 ms in T_2-w images (six patients). Images were acquired before, during, and following the injection of 0.1 mmol kg^{-1} Gd-DOTA (Meglumin-Gadoterat, Laboratoire Guerbet, Aulnay-sous-Bois, Cedex, France). The bolus of contrast agent was administered into the cubital vein with a flow rate of 2–3 ml s^{-1} followed by a flush of 20 ml NaCl. The immediate beginning of the injection of the contrast medium was defined as time = 0.

A 10-mm-thick axial slice through the upper abdomen demonstrating kidneys, spleen, and liver was repeatedly scanned over 4 min 120 consecutive T_2-weighted (one package, interscan delay 2000 ms) and 240 T_1-weighted images (two packages with an interscan delay of 500 ms) with a time gap of 2 min between the two packages in order to obtain late signal intensity changes. Imaging parameters included a FOV of 47 cm, a matrix of 128 × 128, and one NEX. SI values were measured within operator-defined regions of interest (ROI) placed manually over renal cortex and outer and inner renal medulla (so-called o-medulla and i-medulla) spleen and liver. The differentiation of the renal cortex and outer and inner medulla was visually determined on our T_1- and T_2-w images. The size of the ROIs varied among 4 mm^2 in the kidney, 150 mm^2 in the spleen, and 500 mm^2 in the liver. Dynamic SI changes of the various abdominal organs due to the different T_1 and T_2 relaxation times after injection of the contrast agent were evaluated as % SI (procentual difference of the SI values before and after injection of the contrast agent) in each patient, and the mean values of every organ were plotted versus time. These SI values are mean values of each organ averaged in all examined patients. Time = 0 was defined as the immediate beginning of the injection of the contrast medium. Data were only depicted over the first minute of scanning in T_1-w SE-EPI and over the first 2 min in T_2-w SE-EPI, despite a scanning time of several minutes because the late SI values of the various abdominal organs that are not depicted in our figures remained constant.

RESULTS

The results are summarized in Figs. 1 and 2.

Kidneys

The SI alterations in the kidneys were very distinct: On T_1-w images early SI increase was observed in the renal cortex 7 s after Gd-DOTA injection followed by an increase in the outer renal medulla 6 s later (Figs. 3a,b) and in the inner renal medulla 21 s later. Maximal SI in the renal cortex was 153%, in the outer renal medulla 206%, and in the inner renal medulla 188%.

On T_2-w images, a rapid SI decrease in the renal cortex started after 14 s (Figs. 4a,b). It lasted for 30 s, resulting in a minimal SI of 45%, followed again by a moderate increase up to 72% (Fig. 4c). The SI decrease in the outer renal medulla started after 46 s (with minimal SI of 53%, Fig. 4c) and in the inner renal medulla after 70 s (with minimal SI of 48%, Fig. 4d), resulting in a "dark band" migrating from the outer to the inner medulla.

Spleen and liver

In the spleen, the SI increase on T_1-w-images started 15 s after injection of the contrast agent and reached its maximum (175%) 17 s later (Figs. 3a,b). In the liver, the SI increase followed with a delay of 7 s. Peak

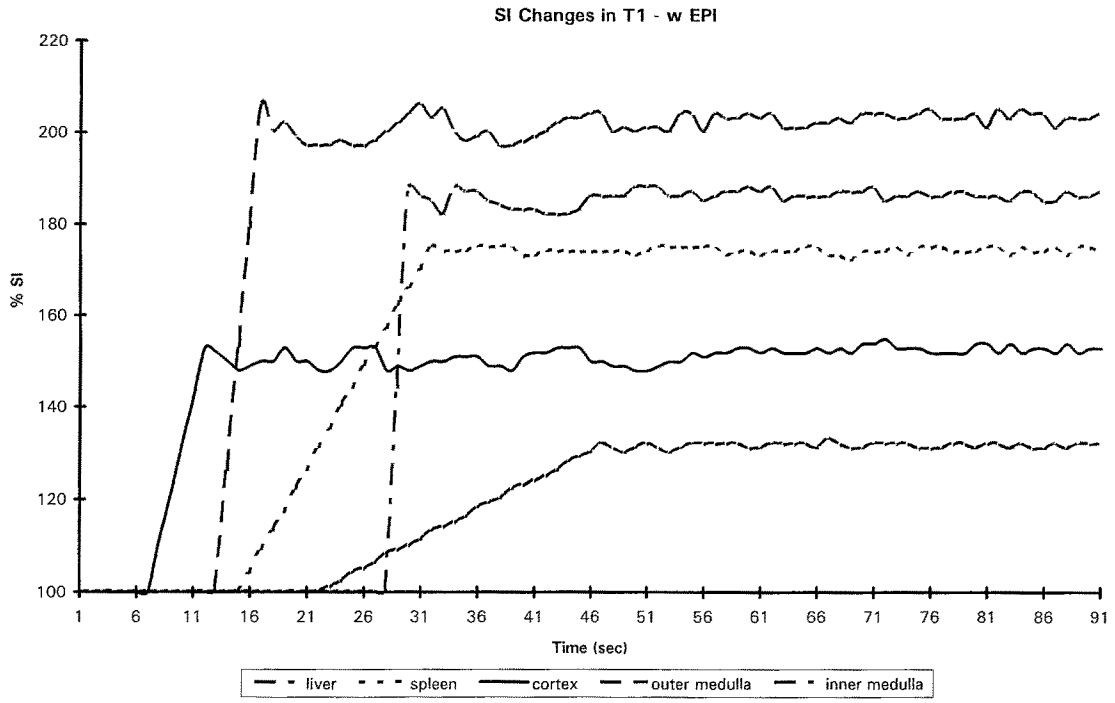

Fig. 1. The time-dependent SI changes expressed as %SI in kidney, liver, and spleen after I.V. injection of Gd-DOTA in T_1-w SE-EPI.

values (132%) were measured after 47 s. On T_2-w images only slight SI changes in the spleen and liver were detectable: A minimal and short-term SI decrease (70%) in the spleen was measurable after 20 s, lasting for 30 s. Finally, the SI increased again up to 100%. A similar SI alteration occurred in the liver: The SI decrease started after 26 s, reached minimal values of 60%, lasted for 30 s, and increased again up to 90% SI. The alterations in the spleen and liver were only measurable but not really visible on the image.

DISCUSSION

Due to its ultrafast acquisition of multiple and consecutive images, EPI is a very accurate method for evalua-

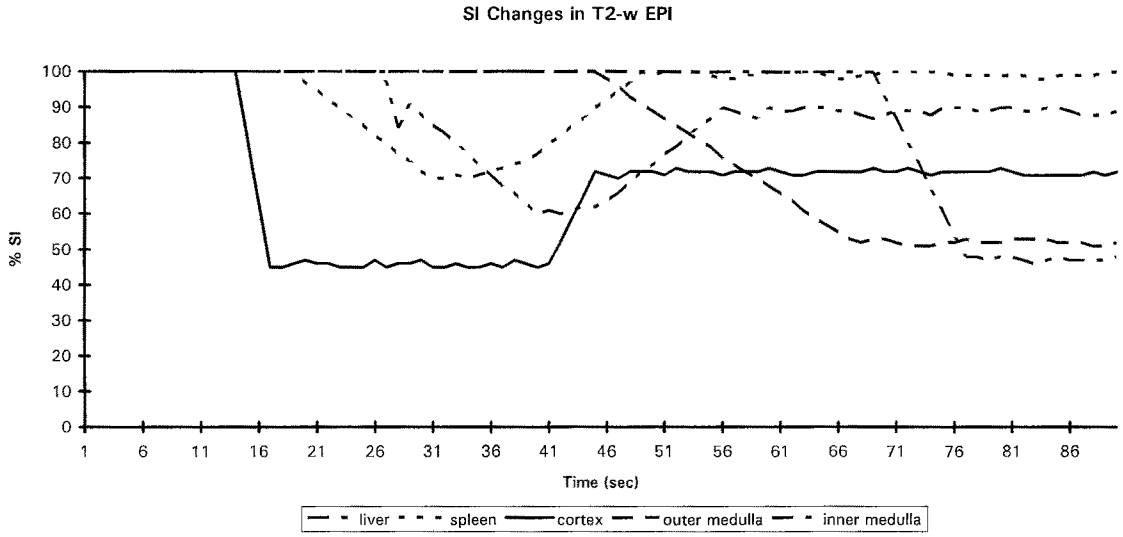

Fig. 2. The time-dependent SI changes expressed in % SI in kidney, liver, and spleen after I.V. injection of Gd-DOTA in T_2-w SE-EPI.

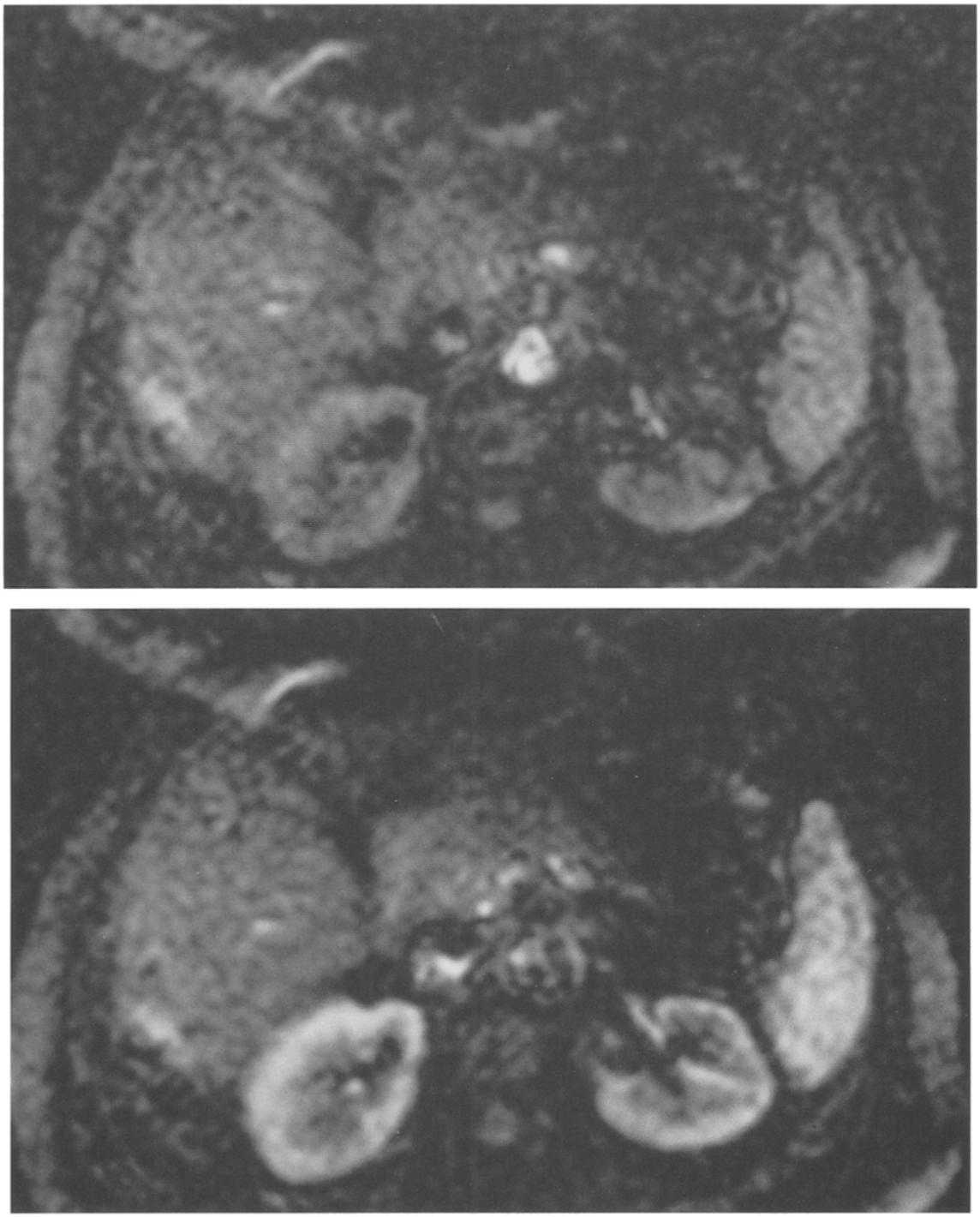

Fig. 3. (a) Axial T_1-w SE-EPI through kidney, spleen, and liver before I.V. injection of Gd-DOTA. (b) Axial T_1-w SE-EPI through kidney, spleen, and liver 20 s after I.V. injection of Gd-DOTA. High signal intensity in the renal cortex, in the outer renal medulla, and in the spleen. No liver enhancement.

tion of the early contrast enhancement and related SI changes after intravenous bolus injection of a paramagnetic extracellular contrast agent such as Gd-DOTA. The pharmacokinetics of Gd-DOTA are similar to those of the first gadolinium complex in clinical use, GD-DTPA [1]. It typically shows a very rapid plasma clearance by renal glomerular filtration, and a fast shifting from the intravascular into the interstitial extracellular compartment. This starts with the first passage and results in a quick equilibration between

the two compartments [1, 4–8]. The tissue concentration of Gd-DOTA is directly related to the administered dose, to the volume of the extracellular space, and to the perfusion (blood flow). It directly influences the SI in the tissue itself: At low concentrations, Gd-DOTA tends to shorten T_1, leading to an increase in SI. As Gd-DOTA concentration increases, T_2 shortening predominates and results in a progressive SI decrease. At higher concentrations, magnetic susceptibility also contributes to a SI reduction in both the tissue and the adjacent areas leading to a further T_2 shortening [4–8]. The strong magnetic susceptibility effect of T_2^*, however, contributes much more effectively to a decrease in SI compared with SI changes due to alterations in the concentration of gadolinium-DOTA. Therefore, SI changes in different tissues immediately after bolus injection are due to alterations in T_1 and T_2 relaxation times in relation to the local concentration of the contrast agent and the imaging sequence used.

EPI is the ideal technique to provide MR images in a very short time. Single-shot EPI allows the acquisition of up to 20 slices per second. The time-dependent early dynamic distribution of a paramagnetic ectracellular contrast agent in various organs can be visually percepted if a single slice is repeatedly scanned several seconds to minutes after bolus injection. However, the rapid repetition of a single image in the same position would lead to very short effective repetition times and, therefore, to important saturation effects with SI decrease.

In our study, early SI changes on T_1- and T_2-w SE-EPI after injection of Gd-DOTA were examined using a standard dosage (0.1 mmol kg^{-1}). In the renal cortex, SI changes on T_1-w images were characterized by an early increase followed immediately by an increase in the outer and then in the inner renal medulla. The maximal values reached were much lower than those reported in a previous study using SE-MRI [8]. This difference is mainly due to the characteristics of the EPI sequence: In any SE-EPI sequence the selected effective TE consists of a spectrum of different TEs resulting in concomitant T_1 and T_2 effects at each selected TR. Therefore, on T_1-w EPI, an additional T_2 effect is always present leading to a SI decrease.

On T_2-w images, SI decreased in the renal cortex and in the outer and inner renal medulla. The SI decrease on T_2-w EPI was due to T_2 shortening and additional susceptibility effects of Gd-DOTA. The plateau of SI on T_1-w images observed in the outer medulla appeared at a higher level when compared with the inner medulla. This relation is reversed on the T_2-w images. These are simple effects of T_1 and T_2 shortening.

In animal and human studies [4–6, 8–11] using dynamic gadolinium-enhanced MR imaging (SE and GE images), similar time-dependent SI changes in the kidneys were reported. The early SI increase in the cortex on T_1-w images corresponds to the arrival of Gd-DOTA in the cortical vessels and glomerular capillaries. The cortical darkening on T_2-w images may be the result of the magnetic susceptibility-induced spin-dephasing effects of Gd-DOTA in the arteriolar and capillary network. The SI decrease on T_2-w EPI first in the outer medulla and later in the inner medulla leads to the formation of a "dark band" that migrates centripetally as the contrast agent traverses the renal tubular system from the cortex to the papilla. Gd-DOTA is progressively concentrated due to water reabsorbtion leading to T_2 shortening effects. Therefore, the time-dependent SI pattern is mostly affected by the intratubular concentration of Gd-DOTA.

The SI changes in the medulla are first visible and also measurable on T_1-w EPI (SI increase) and with a short delay on T_2-w EPI (SI decrease). The initial predominance of the T_1 effect likely reflects the relatively low concentration of Gd-DOTA in the proximal convoluted tubule.

In the spleen, the signal intensity changes on T_1- and T_2-w images were characterized by a slow SI increase on T_1-w images. They were more prominent than those observed in the renal cortex and in the liver.

In the liver, SI changes were similar, but they started later than in the spleen. The peak SI values also occurred later than in the kidney and the spleen and were less prominent. On T_1-w GRE images [8], a more pronounced initial peak enhancement was reported. On T_2-w images, an initial very slight and short-term SI decrease followed by an increase up to almost the initial SI.

The only slight SI alterations of the liver on T_1 and T_2 SE-EPI can be explained by the small extracellular space of the liver tissue, leading to low-contrast agent concentrations.

In our study, the SI peak in liver and spleen were lower compared with those in a study obtained with T_1-w GRE sequences [8]. This is again probably due to the T_2 effect that is always present on T_1-w EPI, leading to a SI decrease as mentioned earlier.

In summary, EPI allows one to analyze the early kinetics of Gd-DOTA in various abdominal organs after intravenous injection. The associated changes in T_1 and T_2 relaxation times depend on organ perfusion and Gd-DOTA tissue concentration. The conspicuous time-dependent SI alterations in the kidney probably

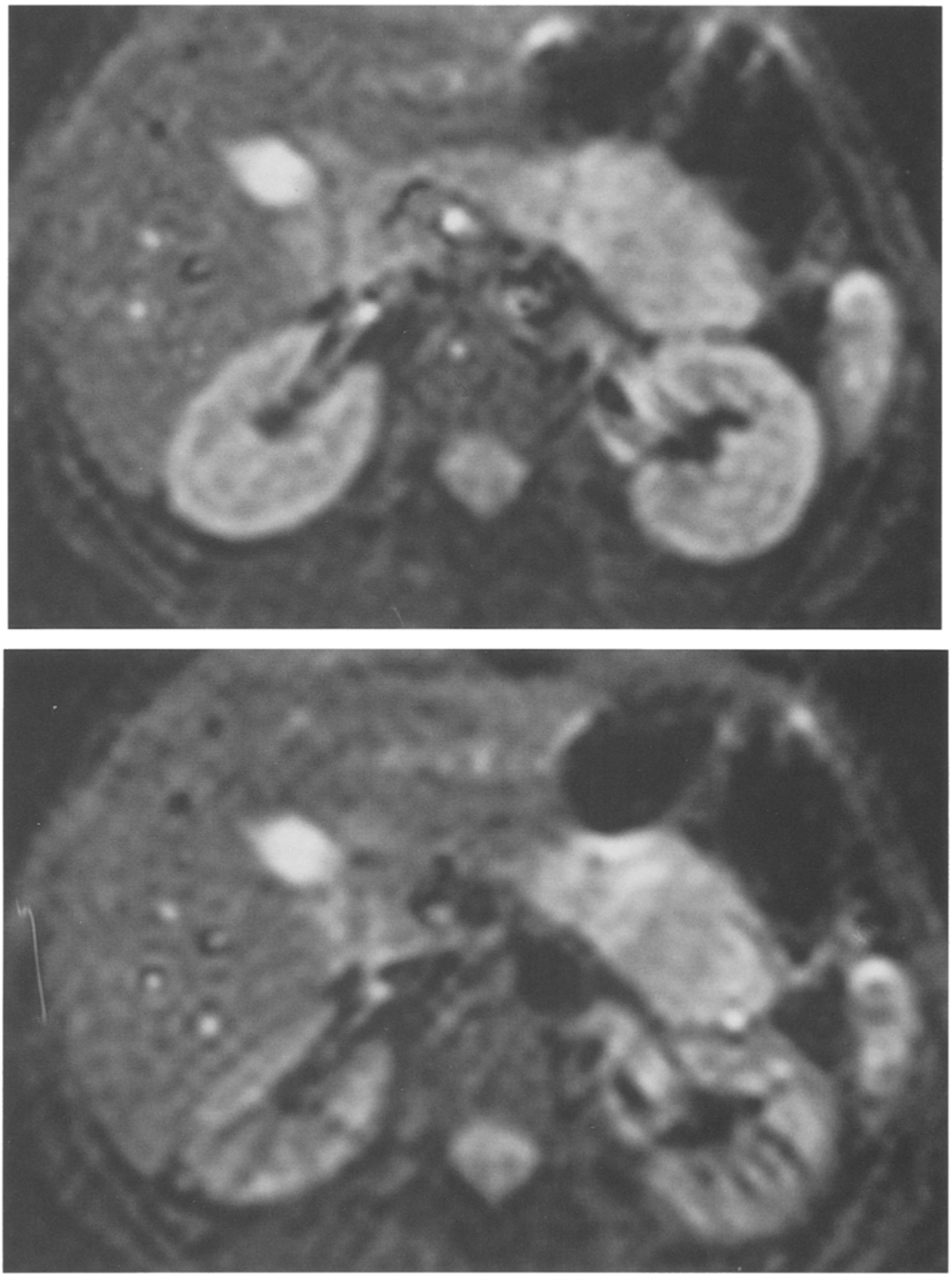

Fig. 4. Axial T_2-w SE-EPI through kidney, spleen, and liver before (a) and 14 s (b), 50 s (c) and 75 s (d) after I.V. injection of Gd-DOTA. (a) High signal intensity in the renal cortex. Intermediate signal intensity in outer and inner renal medulla. (b) Low signal intensity in the renal cortex. No SI changes in the renal medulla.

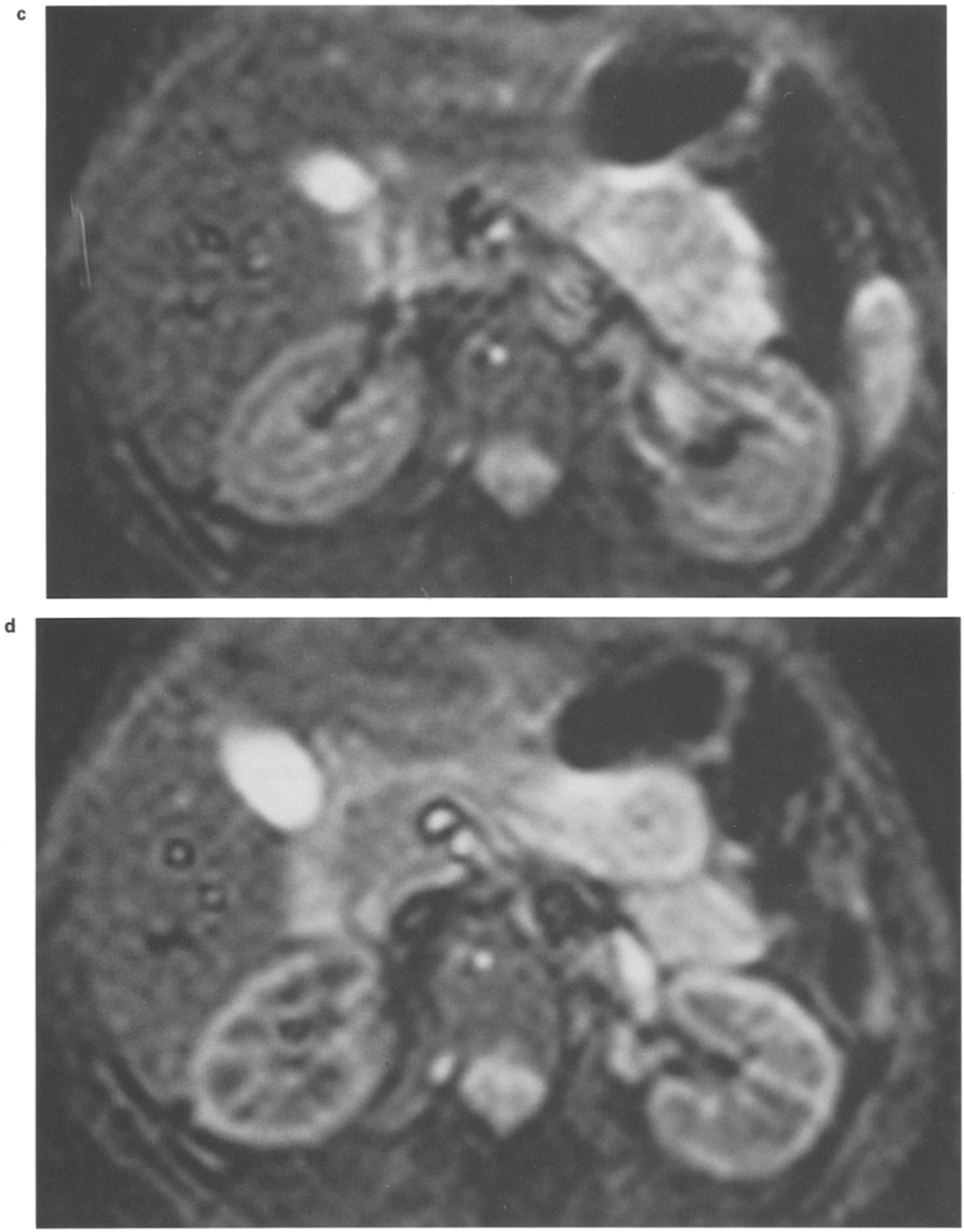

Fig. 4. (c) High signal intensity in the renal cortex. A hypointense rim in the outer renal medulla. No changes in the inner renal medulla. (d) The renal cortex remains hyperintense. Low signal intensity both in the outer and inner renal medulla.

reflect its concentrating ability, and their analysis may be valuable for functional examinations. However, despite our study, not all time-dependent SI changes on T_1- and T_2-w SE-EPI images after the I.V. injection of gadolinium-DOTA can be physiologically explained, and additional examinations performed with different concentrations of gadolinium-DOTA and different TR/TE parameters must help to give more accurate explanations for these unique time-dependent and gadolinium-DOTA-dependent SI curves on T_1- and T_2-w images.

Further investigations have to be made in order to assess the clinical value of the determination of the very early SI changes in the various abdominal organs over the first few minutes; for example, in the characterization of tumorous and infectious lesions.

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