Optimization of Look-Locker Turbo-Field Echo-Planar Imaging and Evaluation of Its Accuracy in Head and Neck 3D $T_1$ Mapping

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Purpose: We present a sequence for $T_1$ relaxation-time mapping that enables a rapid and accurate measuring. The sequence is based on the Look-Locker method by employing turbo-field echo-planar imaging (TFEPI) acquisitions and time to free relaxation after constant application of the radiofrequency (RF) pulses. We optimized the sequence, and then evaluated the accuracy of the method in imaging of head and neck.

Materials and Methods: The method was implemented on a standard clinical scanner, and the accuracy of the $T_1$ value was evaluated against that with the two-dimensional (2D) inversion recovery method.

Results: The percentage errors of the $T_1$ value, as validated by phantom imaging measurements, were 3.1% for slow-relaxing compartments ($T_1 = 2736$ msec) and 1.1% for fast-relaxing compartments ($T_1 = 264.2$ msec).

Conclusion: We demonstrated a fast 3D sequence to obtain multiple slices, based on the Look-Locker method for $T_1$ measurement, which provided a rapid and accurate way of measuring the spin-lattice relaxation time. An acquisition time of approximately 5 min was achieved for $T_1$ mapping; in principle, this can provide head and neck coverage with 15 slices.

Keywords: $T_1$ mapping, LL-TFEPI, head and neck, Look-Locker

Introduction

Several of the new magnetic resonance (MR) applications require quantitative measurement of the spin-lattice relaxation time ($T_1$) in three dimensions (3Ds) with relatively short acquisition times. For example, quantitative tracer kinetic studies, in which vascular parameters such as blood volume and capillary permeability are calculated from dynamic contrast-enhanced MR data, require fast and accurate measurement of tissue $T_1$ values. Before application of a tracer kinetic model, tissue enhancement following contrast agent administration must be converted into contrast agent concentration, and it can be shown that this calibration depends strongly on the pre-contrast tissue $T_1$ value.1–5 Ideally, tracer kinetic studies should be done in 3D for complete characterization of a lesion, or to locate small lesions not apparent in pre-contrast scans, or to examine multiple lesions in one study. Moreover, tissue $T_1$ measurement in the head and neck should be done in less than 5 min for studies to have clinically realistic acquisition times.

One of the major problems encountered in making accurate $T_1$ maps is the long imaging time required. For good accuracy over a wide range of $T_1$ values, multiple points on the $T_1$ recovery curve must be sampled. If a conventional two-dimensional (2D) inversion recovery sequence is used, data acquisition for each slice can take a few hours. Several schemes have been developed for rapid $T_1$ mapping in 2D in which multiple points
on the recovery curve are sampled. These techniques include methods based on the work of Look-Locker, snapshot-fast low angle shot (snapshot-FLASH), a mixed sequence method, and a variable flip angle (VFA) method.

The major advantages of using a sequence based on the Look-Locker method and employing turbo-field echo-planar imaging (TFEPI) acquisitions are that the acquisition time is short and the T₁ relaxation behavior has been well-characterized. TFEPI combines turbo-field echo (TFE) and echo-planar imaging (EPI). A theoretical analysis has shown that if the Look-Locker technique is used, rather than the more time-consuming conventional inversion recovery method, T₁ values can be measured quickly with no penalty to the signal-to-noise ratio of the calculated T₁ map. Other authors have demonstrated a high degree of accuracy and precision achievable experimentally with this technique. However, it is difficult to apply the Look-Locker technique of multiple slices clinically, because this technique is a continuous application of the radiofrequency (RF) pulses used for imaging, and if inversion recovery pulse interval is same, sampling time becomes insufficient.

Here, we introduce a fast 3D technique for rapidly acquiring data of multiple slices for accurate T₁ mapping. This technique is based on the principles of the two-dimensional Look-Locker T₁ measurement scheme, and employs turbo-field echo-planar imaging (TFEPI) acquisitions and time to free relaxation after constant application of the radiofrequency (RF) pulses. The acquisition time needed for volumetric T₁ mapping has been shortened considerably by segmenting the acquisition of the kᵢ phase encode lines. This technique is similar to that which might be obtained by modifying snapshot-FLASH based T₁ measurement schemes for 3D. However, there is no delay between acquisition of successive volumes and T₁ relaxation is governed by the principles introduced by Look and Locker. We optimized the sequence on the basis of the Look-Locker method, and then evaluated the accuracy of the method in imaging of head and neck.

**Theory**

In this method, the relaxation process is influenced by constant application of the RF pulses. The effective longitudinal relaxation is determined by the effective longitudinal relaxation time T₁*, which is smaller than T₁. The longitudinal magnetization M(t) approaches a saturation value M₀*, which is smaller than the equilibrium value M₀. The turbo-field echo (TFE) factor is 3 in this case; tᵣ is recovery period.

Fig. 1. Representation of the recovery of longitudinal magnetization following an inversion pulse. This technique is based on the principles of the two-dimensional Look-Locker T₁ measurement scheme, and employs turbo-field echo-planar imaging (TFEPI) acquisitions and time to free relaxation after constant application of the radiofrequency (RF) pulses. The relaxation process of the Look-Locker sequence is influenced by constant application of the RF pulses used for imaging after inversion pulse. The longitudinal magnetization M(t) approaches a saturation value M₀*, which is smaller than the equilibrium value M₀. The turbo-field echo (TFE) factor is 3 in this case; tᵣ is recovery period.

The relaxation process is described by the formula

\[
M(t) = M_0^* - (M_0 + M_0^*) \cdot \exp \left(-\frac{t}{T_1^*}\right)
\]

(1)

The effective longitudinal relaxation time T₁* is given by

\[
\frac{1}{T_1^*} = \frac{1}{T_1} - \frac{1}{TR} \ln(\cos \alpha)
\]

(2)

where \(\alpha\) is the flip angle.
The saturation value $M_0^*$ of the longitudinal magnetization is given by

$$M_0^* = M_0 \cdot \frac{1 - \exp \left(-\frac{TR}{T_1^*} \right)}{1 - \exp \left(-\frac{TR}{T_1^*} \right)}$$ (3)

This method is applicable only if the condition $TR < T_1^*$ holds. Thus, Eq. (3) may be simplified to

$$M_0^* = M_0 \cdot \frac{T_1^*}{T_1}$$ (4)

For the evaluation of $T_1$, a three-parameter fit of the image signal intensities is performed pixelwise according to the equation

$$M(t) = A - B \cdot \exp \left(-\frac{t}{T_1^*} \right)$$ (5)

Comparison with the above equations yields

$$A = M_0^*, \quad B = M_0 + M_0^*$$ (6)

Thus, $T_1$ may be calculated directly from the fit parameters

$$T_1 = T_1^* \cdot \frac{B}{A} - 1$$ (7)

The results of the pixelwise calculation can be displayed in a quantitative $T_1$ map. Of note, the method does not require knowledge of the flip angle $\alpha$.

**Materials and Methods**

We tested the method on a phantom and a human in a 1.5-T whole-body scanner (Intera Achieva 1.5-T Nova, Philips, The Netherlands) with a maximum gradient strength of 66 mT/m and a gradient slew rate of 160 mT/m/ms using a Philips 8-channel SENSE head coil.

We measured $T_1$ values using magnitude image. The maps of $T_1^*$, $M_0^*$, and $M_0$ were obtained by fitting the image signal intensities on pixelwise basis to Eq. (5) using the nonlinear least-squares method by MATLAB R2014b (MathWorks, Natick, MA, USA). Moreover, $T_1$ map was calculated by using Eqs. (6) and (7) with maps of $T_1^*$, $M_0^*$, and $M_0$.

**Phantom study**

To validate the $T_1$ values resulting from the sequence to be based on the Look-Locker method as described above, we applied standard inversion recovery method to a multi-compartment phantom. The phantom consists of six cylindrical sample bottles filled with water and different concentrations of gadoteridol (Gd-HPDO3A, ProHance, Eisai Co. Ltd., Tokyo, Japan). The gadoteridol concentrations are 0.05, 0.1, 0.2, 0.5, and 1.0 mmol/L, respectively.

The 2D inversion recovery sequence is a simple acquisition with an inversion recovery pulse before an excitation pulse. The imaging parameters for acquisition of a single image are as follows and shown in Table 1: repetition time (TR) 15000 msec; echo time (TE) 20 msec; field of view (FOV) 230 × 196 mm; acquisition matrix 256 × 218; acquisition pixel size 0.9 × 0.9 mm; recon matrix 256 × 218; recon pixel size 0.9 × 0.9 mm; 1 slice with a thickness of 5 mm; band width 64.3 Hz; and sampling points at 50, 100, 200, 500, 1000, 2000, 3000, and 5000 msec. The acquisition time for this sequence is 7 h 14 min. Each measurement was performed three times, and the averaged values were used for the comparison.

To verify that we had properly chosen the EPI factor which is the number of k-space profiles collected per excitation, TFE factor which is the number of k-space profiles collected per sampling point, and recovery period ($t_r$) which is time to free relaxation after constant application of the RF pulses, for the phantom measurements using the Look-Locker sequence, the experiments were repeated with all parameters held constant except for EPI factor, TFE factor, and $t_r$. Three values of EPI factor (1, 3, and 11) were chosen. Because each acquisition time was the same time, three values of TFE factor (33, 11, and 3) were chosen. Furthermore, at the end of the train of $\alpha$-pulses, an undisturbed recovery period was optionally inserted to allow the recovery of longitudinal magnetization before the next inversion pulse. Two values of $t_r$ (3136 and 4993 msec) were chosen.

The Look-Locker sequence was used to obtain images to perform fitting of the $T_1$ relaxation of the doped water in the different bottles. The measurement parameters are as follows and shown in Table 1: TR shortest (6.5, 11, and 22 msec); TE shortest (3.2, 4.8, and 11 msec); FOV 230 × 196 mm; acquisition matrix 192 × 127; acquisition pixel size 1.2 × 1.54 mm; recon matrix 256 × 218; recon pixel size 0.9 × 0.9 mm; 15 slices with a thickness of 5 mm; band width 229.2, 151.2, and 54.7 Hz; flip angle 10°; inversion recovery pulse interval 7000 msec; and sampling points is shown in Table 1. The acquisition time for this sequence is 5 min 3 sec. To demonstrate the accuracy of the $T_1$ values obtained by using the Look-Locker method, we compared the resultant $T_1$ values with those obtained from 2D inversion recovery method measurements and calculated the percentage errors. In each bottle a circular region of interest (ROI) comprising 15 × 15 pixels was used to calculate a mean $T_1$ value.

**Volunteer study**

We performed a study on a single healthy volunteer by using the 2D turbo inversion recovery and optimized 3D Look-Locker methods after obtaining their informed consent as required by our institutional review board. The 2D turbo inversion recovery
Table 1. The imaging parameters for acquisition of the two-dimensional (2D) inversion recovery, the 2D turbo inversion recovery, and the 3D Look-Locker sequences

| Parameter                      | 2D inversion recovery sequence | 2D turbo inversion recovery sequence | 3D Look-Locker sequence |
|--------------------------------|-------------------------------|------------------------------------|------------------------|
| TR (msec)                      | 15000                         | 10000                              |                        |
| TE (msec)                      | 20                            | 20                                 |                        |
| FOV (mm)                       | 230 × 196                     | 230 × 196                          |                        |
| Acquisition matrix             | 256 × 218                     | 192 × 123                          |                        |
| Acquisition pixel size (mm)    | 0.9 × 0.9                     | 1.2 × 1.59                         |                        |
| Recon matrix                   | 256 × 218                     | 256 × 218                          |                        |
| Recon pixel size (mm)          | 0.9 × 0.9                     | 0.9 × 0.9                          |                        |
| Slice thickness (mm)           | 5                             | 5                                  |                        |
| TSE factor                     | 1                             | 8                                  |                        |
| Band width (Hz)                | 64.3                          | 477.8                              |                        |
| Sampling point (msec)          | 50, 100, 200, 500, 1000, 2000, 5000 | 50, 100, 200, 500, 1000, 2000, 5000 |                        |
| Scan time                      | 7 h 14 min                    | 10 min 30 sec                      |                        |

Continued
Fig. 2. (a) M₀*, (b) M₀, (c) T₁*, and (d) T₁ map of a multi-compartment phantom, as generated from images acquired with the Look-Locker sequence. The locations of bottles 1, 2, 3, 4, 5, and 6 correspond to water and nominal gadoteridol concentrations of 0.05, 0.1, 0.2, 0.5, and 1.0 mmol/L, respectively. There was ghost artifact, a little.

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Table 1. Continued
3D Look-Locker sequence

| Parameter                        | M₀* | M₀ | T₁* | M₀* | M₀ | T₁ |
|----------------------------------|-----|----|-----|-----|----|----|
| Band width (Hz)                  | 229.2 | 151.2 | 54.7 | 229.2 | 151.2 | 54.7 |
| Flip angle (°)                   | 10  |    |    |     |    |    |
| IR pulse interval (msec)         | 7000 |    |    |     |    |    |
| tᵣ (msec)                       | 3136 | 4993 |    |     |    |    |
| Sampling point (msec)            | 14, 240, 467, ..., 3638 | 14, 134, 255, ..., 3744 | 14, 110, 206, ..., 3768 | 14, 235, 457, ..., 1786 | 14, 131, 248, ..., 1890 | 14, 114, 213, ..., 1908 |
| Sampling interval (msec)         | 227  | 120 | 96  | 222 | 117 | 100 |
| Scan time                        | 5 min 3 sec |    |    |     |    |    |

sequence parameters for acquisition of a single image are as follows and shown in Table 1: TR 10000 msec; TE 20 msec; FOV 230 × 196 mm; acquisition matrix 192 × 123; acquisition pixel size 1.2 × 1.59 mm; recon matrix 256 × 218; recon pixel size 0.9 × 0.9 mm; 1 slice with a thickness of 5 mm; TSE factor 8; band width 477.8 Hz; and sampling points at 50, 100, 200, 500, 1000, 2000, and 5000 msec. The acquisition time for this sequence is 10 min 30 sec. To demonstrate the accuracy of the T₁ values obtained by using the 2D turbo inversion recovery method, we compared the resultant T₁ values with those obtained from 2D inversion recovery method measurements and calculated the percentage errors in the phantom study.

The 3D Look-Locker sequence parameters that we chose were those optimized in the phantom study. We compared the T₁ values of the cerebrospinal fluid (CSF), sternocleidomastoid muscle (SCM), and parotid gland (PG) of the healthy volunteer with those obtained by using 2D turbo inversion recovery measurements and calculated the percentage errors.

Results

We calculated T₁ maps of the multi-compartment phantom by using data acquired with the Look-Locker method (Fig. 2). Tables 2 and 3 give the T₁ values (Table 2) and percentage errors (Table 3) for the phantom measurements resulting from the 2D inversion recovery, 2D turbo inversion recovery, and 3D Look-Locker measurements. The 2D inversion recovery measurements served as a reference for all other experiments. The locations of “bottle 1,” “bottle 2,” “bottle 3,” “bottle 4,” “bottle 5,” and “bottle 6” correspond to water and the nominal gadoteridol concentrations of 0.05, 0.1, 0.2, 0.5, and 1.0 mmol/L, respectively (Fig. 2). There was good agreement between the T₁ values from the 2D inversion recovery measurements and those from the 2D turbo inversion recovery measurements.

With tᵣ = 3136 msec, there was not good agreement between the 2D inversion recovery measurements and the 3D Look-Locker measurements in water and gadoteridol at the nominal concentrations of 0.05 mmol/L. With EPI factor = 1, TFE factor = 33, and EPI factor = 11, TFE factor = 3, there was not agreement in gadoteridol at the nominal concentrations of 0.5 and 1.0 mmol/L. However, with EPI factor = 3, TFE factor = 11, and tᵣ = 4993 msec, there was good agreement. These parameters gave the best agreement. We then compared the T₁ values for the phantom measurements.
Table 2. Comparison of calculated $T_1$ values (ms) resulting from application of the two-dimensional (2D) inversion recovery method, the 2D turbo inversion recovery method, and the 3D Look-Locker method for the different bottles comprising the phantom shown in Fig. 2. Values are means ± standard deviations of $T_1$ values in a homogeneous region of interest.

|                               | 2D inversion recovery method | T1 (ms) |
|-------------------------------|-----------------------------|---------|
|                               |                             |         |
| Water                         |                             | 2736.3 ± 13.1 |
| Gd_0.05 mmol/L                |                             | 1904.8 ± 7.6 |
| Gd_0.1 mmol/L                 |                             | 1157.6 ± 4.3 |
| Gd_0.2 mmol/L                 |                             | 672.9 ± 1.9  |
| Gd_0.5 mmol/L                 |                             | 408.1 ± 1.0  |
| Gd_1.0 mmol/L                 |                             | 264.2 ± 0.8  |

|                               | 2D turbo inversion recovery method | T1 (ms) |
|-------------------------------|----------------------------------|---------|
|                               |                                  |         |
| Water                         |                                  | 2652.4 ± 39.1 |
| Gd_0.05 mmol/L                |                                  | 1906.6 ± 21.5 |
| Gd_0.1 mmol/L                 |                                  | 1143.2 ± 9.0 |
| Gd_0.2 mmol/L                 |                                  | 670.4 ± 4.5  |
| Gd_0.5 mmol/L                 |                                  | 402.8 ± 1.7  |
| Gd_1.0 mmol/L                 |                                  | 265.1 ± 2.3  |

|                               | 3D Look-Locker method | T1 (ms) |
|-------------------------------|-----------------------|---------|
|                               |                       |         |
| t_r = 3136 ms                 | EPI factor 1          | 2240.0 ± 115.8 |
|                               | TFE factor 33         | 2156.0 ± 75.4 |
|                               | TFE factor 11         | 2466.9 ± 154.1 |
| Gd_0.05 mmol/L                | EPI factor 3          | 1580.5 ± 41.5 |
|                               | TFE factor 11         | 1677.9 ± 103.4 |
|                               | TFE factor 3          | 1676.5 ± 57.7 |
| Gd_0.1 mmol/L                 |                       | 1117.2 ± 21.7 |
|                               |                       | 1143.3 ± 27.8 |
|                               |                       | 1140.5 ± 28.5 |
| Gd_0.2 mmol/L                 |                       | 703.9 ± 13.9  |
|                               |                       | 686.2 ± 14.2  |
|                               |                       | 637.6 ± 13.2  |
| Gd_0.5 mmol/L                 |                       | 442.1 ± 6.5   |
|                               |                       | 410.0 ± 9.5   |
|                               |                       | 365.2 ± 9.2   |
| Gd_1.0 mmol/L                 |                       | 307.1 ± 4.9   |
|                               |                       | 271.3 ± 4.5   |
|                               |                       | 226.4 ± 7.1   |

|                               | t_r = 4993 ms         | EPI factor 1 | 2822.0 ± 210.6 |
|                               |                       | TFE factor 33| 2652.2 ± 81.8  |
|                               |                       | TFE factor 11| 2803.2 ± 231.1 |
| Gd_0.05 mmol/L                |                       | 1821.2 ± 88.9|
|                               |                       | 1922.1 ± 79.1|
|                               |                       | 1807.0 ± 66.7|
| Gd_0.1 mmol/L                 |                       | 1170.0 ± 28.2|
|                               |                       | 1187.5 ± 22.5|
|                               |                       | 1181.2 ± 37.7|
| Gd_0.2 mmol/L                 |                       | 706.0 ± 9.4  |
|                               |                       | 691.1 ± 12.5  |
|                               |                       | 631.3 ± 13.5  |
| Gd_0.5 mmol/L                 |                       | 453.5 ± 6.9   |
|                               |                       | 411.5 ± 8.0   |
|                               |                       | 375.5 ± 12.0  |
| Gd_1.0 mmol/L                 |                       | 308.7 ± 4.5   |
|                               |                       | 267.2 ± 4.5   |
|                               |                       | 226.6 ± 6.0   |

EPI, echo-planar imaging; TFE, turbo-field echo; $t_r$, recovery period

resulting from the 2D inversion recovery, the 2D turbo inversion recovery, and the optimized 3D Look-Locker measurements (Fig. 3). A high correlation was observed between the results obtained with the three methods.

We next calculated the $T_1$ map of a healthy volunteer from data obtained by using the optimized 3D Look-Locker method (Fig. 4). $T_1$ measurements made by using the 2D turbo inversion recovery and optimized 3D Look-Locker sequences are compared...
Table 3. Comparison of percentage errors of $T_1$ values obtained from by using the two-dimensional (2D) inversion recovery method, the 2D turbo inversion recovery method, and the 3D Look-Locker method. The 2D inversion recovery measurements served as a reference. Values are percentage errors of $T_1$ values in a homogeneous region of interest.

| 2D turbo inversion recovery method | Percentage error (%) |
|----------------------------------|-----------------------|
| Water                            | 3.1                   |
| Gd_0.05 mmol/L                   | 0.1                   |
| Gd_0.1 mmol/L                    | 1.2                   |
| Gd_0.2 mmol/L                    | 0.4                   |
| Gd_0.5 mmol/L                    | 1.3                   |
| Gd_1.0 mmol/L                    | 0.3                   |

| 3D Look-Locker method            | Percentage error (%) |
|----------------------------------|-----------------------|
| EPI factor 1                     |                       |
| TFE factor 33                    |                       |
| tf_3136 ms                       |                       |
| Water                            | 18.1                  |
| Gd_0.05 mmol/L                   | 17.0                  |
| Gd_0.1 mmol/L                    | 3.5                   |
| Gd_0.2 mmol/L                    | 4.6                   |
| Gd_0.5 mmol/L                    | 8.3                   |
| Gd_1.0 mmol/L                    | 16.3                  |
| EPI factor 3                     | 21.2                  |
| TFE factor 11                    | 11.9                  |
| tf_4993 ms                       |                       |
| Water                            | 3.1                   |
| Gd_0.05 mmol/L                   | 4.4                   |
| Gd_0.1 mmol/L                    | 1.1                   |
| Gd_0.2 mmol/L                    | 4.9                   |
| Gd_0.5 mmol/L                    | 11.1                  |
| Gd_1.0 mmol/L                    | 16.9                  |
| EPI factor 11                    | 9.8                   |
| TFE factor 3                      | 12.0                  |
| tf_13136 ms                       |                       |
| Water                            | 18.1                  |
| Gd_0.05 mmol/L                   | 17.0                  |
| Gd_0.1 mmol/L                    | 3.5                   |
| Gd_0.2 mmol/L                    | 4.6                   |
| Gd_0.5 mmol/L                    | 8.3                   |
| Gd_1.0 mmol/L                    | 16.3                  |
| EPI factor 11                    | 21.2                  |
| TFE factor 3                      | 11.9                  |
| tf_4993 ms                       |                       |
| Water                            | 3.1                   |
| Gd_0.05 mmol/L                   | 4.4                   |
| Gd_0.1 mmol/L                    | 1.1                   |
| Gd_0.2 mmol/L                    | 4.9                   |
| Gd_0.5 mmol/L                    | 11.1                  |
| Gd_1.0 mmol/L                    | 16.9                  |
| EPI factor 3                      | 21.2                  |
| TFE factor 11                    | 11.9                  |

EPI, echo-planar imaging; TFE, turbo-field echo; $t_r$, recovery period

Fig. 3. Comparison of $T_1$ values of the different bottles comprising the phantom with those obtained by using the two-dimensional (2D) inversion recovery (IR) method, 2D turbo inversion recovery method, and optimized 3D Look-Locker method.

in Table 4 and Fig. 5 for ROIs in CSF, sternocleidomastoid muscle, and parotid gland. There was a good correlation between the $T_1$ measurements made by using the two methods.

Discussion

There is great interest in fast $T_1$ mapping sequences, particularly for the diagnosis of different diseases, MR temperature monitoring, studies of intra- and extracellular water discrimination, and quantification of regional blood flow. All these measurements require highly accurate $T_1$ values obtained with clinically acceptable acquisition times and with high in-planar resolution. The snapshot-FLASH sequence provides accurate and precise $T_1$ mapping with

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Table 4. Comparison of calculated T<sub>1</sub> values (ms) and their percentage errors obtained by using the two-dimensional (2D) turbo inversion recovery method and optimized 3D Look-Locker (3D-LL) method in a healthy volunteer. Values are means ± standard deviations of T<sub>1</sub> values and percentage errors in a homogeneous region of interest.

|            | T<sub>1</sub> (ms)     | Percentage error (%) |
|------------|-----------------------|----------------------|
|            | 2D-turbo IR           | 3D-LL                |
| CSF        | 3484.5 ± 392.3         | 3350.8 ± 399.1       | 3.8       |
| SCM        | 848.0 ± 72.1           | 894.0 ± 64.5         | 5.4       |
| PG         | 497.3 ± 80.5           | 518.7 ± 74.3         | 4.3       |

CSF, cerebrospinal fluid; IR, inversion recovery; SCM, sternocleidomastoid muscle; PG, parotid gland.

Fig. 4. T<sub>1</sub> map of a healthy volunteer, obtained by using the optimized three-dimensional Look-Locker sequence and the following parameters: repetition time (TR) 11 msec; echo time (TE) 4.8 msec; field of view (FOV) 230 × 196 mm; acquisition matrix 192 × 127; acquisition pixel size 1.2 × 1.54 mm; recon matrix 256 × 218; recon pixel size 0.9 × 0.9 mm; 15 slices with a thickness of 5 mm; echo-planar imaging (EPI) factor 3; turbo-field echo (TFE) factor 11; band width 151.2 Hz; flip angle 10°; inversion recovery (IR) pulse interval 7000 msec; recovery period (t<sub>r</sub>) 4993 msec; sampling points at 117 msec intervals (14, 131, 248, …, 1890 msec). The acquisition time for this sequence was 5 min 3 sec.

Fig. 5. Comparison of T<sub>1</sub> values of the cerebrospinal fluid (CSF), sternocleidomastoid muscle (SCM), and parotid gland (PG) of a healthy volunteer with those obtained by using the two-dimensional (2D) turbo inversion recovery method and optimized 3D Look-Locker (3D-LL) method.

The Look-Locker sequence has made it possible to measure T<sub>1</sub> values in a 3D volume in approximately 5 min with less than 3.1% error, in the case of T<sub>1</sub> values between 264.2 and 2736 msec. We have found the performance of the sequence to be relatively sensitive to pulse sequence parameters. We recommend using t<sub>r</sub> = 4993 msec, EPI factor = 3, and TFE factor = 11 for optimum accuracy of the T<sub>1</sub> measurements. In the case of fast-relaxing compartments, the accuracy of T<sub>1</sub> values declined using TFE factor = 33, because sampling intervals of data acquisitions after inversion recovery pulse are long for fast-relaxing compartments. Moreover, EPI is highly sensitive to static magnetic field inhomogeneities, and increases chemical shift artifact (Fig. 6). This is caused by the accumulation of a phase shift. The EPI factor is one of the causes of this accumulation. In the imaging of...
phantom study, there was ghost artifact (Fig. 2). This is also dependent on EPI factor, but this did not have a serious problem of imaging to measure $T_1$ values in the imaging of volunteer study (Fig. 4). Although, $T_1$ values of parotid gland in the volunteer study were shorter than those of previous study. The reason may be that errors due to the examination of a single volunteer, imaging distortion due to the EPI factor, and changes in the signal intensity due to the phase difference between water and fat by the setting of TE had an influence on the resultant $T_1$ values. In the case of slow-relaxing compartments, the accuracy declined using $t_r = 3136$ msec, because the longitudinal magnetization $M(t)$ did not sufficiently recover to the equilibrium value $M_0$. The longitudinal magnetization $M(t)$ should recover not to the saturation value $M'_0$ but to the equilibrium value $M_0$ because fitting of the recovery curve is done by using Eq. (1). In the case of optimized parameters, we thought the longitudinal magnetization $M(t)$ of slow-relaxing compartments recovers to the equilibrium value $M_0$ sufficiently, because $T_1$ value which is changed by scan parameters was very short ($T_1$ value of water = 541.2 msec), and time ($t_r$) to free relaxation after constant application of the RF pulses was long enough. Therefore, the accurate $T_1$ mapping obtained by using the 3D Look-Locker method needs optimal sampling points and a long enough time ($t_r$) to free relaxation. Moreover, the degree of local imaging distortion, chemical shift artifact, and ghost artifact is reduced sufficiently by using EPI factor = 3 in the imaging of volunteer study (Figs. 4, 7). In this study, we did not examine errors due to flip angle and RF inhomogeneities in detail because that these errors do not affect $T_1$ values is implicated by the theoretical formula, and the difference of $T_1$ values in each slice was less than 1.1% for bottle phantom ($T_1 = 396.6$ msec). Because accuracy, scan time, and artifact are changed by scan parameters, these parameters should be chosen to suit the clinical situation.

**Conclusion**

A fast 3D sequence to obtain multiple slices, based on the Look-Locker method for $T_1$ measurement, provided a rapid and accurate way of measuring the spin-lattice relaxation time. The percentage errors of the $T_1$ values validated by phantom imaging measurements...
were 3.1% for slow-relaxing compartments (water, $T_1 = 2736$ msec) and 1.1% for fast-relaxing compartments (Gd-1.0 mmol/L, $T_1 = 264.2$ msec). An acquisition time of approximately 5 min was achieved for $T_1$ mapping; in principle, this can provide head and neck coverage with 15 slices.

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