Original Research

Sensory Perceptions of Individuals Exposed to the Static Field of a 7T MRI: A Controlled Blinded Study

Björn Friebe, MD,[1]* Astrid Wollrab, MS,[2] Markus Thormann, MD,[1]
Katharina Fischbach, MD,[1] Jens Ricke, MD,[1] Marcus Grueschow, PhD,[3]
Siegfried Kropf, PhD,[4] Frank Fischbach,[1] and Oliver Speck, PhD[2,5]

Purpose: To determine the subjective experience of subjects undergoing 7T magnetic resonance imaging (MRI) compared to a mock scanner with no magnetic field.

Methods and Materials: In all, 44 healthy subjects were exposed to both the B_0 field of a 7T whole-body MRI and a realistic mock scanner with no magnetic field. Subjects were blinded to the actual field strength and no scanning was performed. After exposure, subjects rated their experience of potential sensory perceptions.

Results: The most frequently observed side effect was vertigo while entering the gantry, which was reported by 38.6% ($n = 17$). Other frequent side effects were the appearance of phosphenes (18.2%, $n = 8$), thermal heat sensation (15.9%), unsteady gait after exposure (13.6%, $n = 6$), and dizziness (13.6%). All side effects were reported significantly more often after 7T exposure. Nine subjects (20.5%) did not report any sensory perceptions at all, ie, neither in the 7T scanner nor in the mock scanner.

Conclusion: Light, acute, and transient sensory perceptions can occur in subjects undergoing ultrahighfield MRI, of which vertigo seems to be the most frequently reported. Possible psychological effects might contribute to the emergence of such sensory perceptions, as some subjects also reported them to appear in a realistic mock scanner with no magnetic field.

Key Words: magnetic resonance imaging; ultrahighfield MRI; MRI safety; vertigo; 7T

J. Magn. Reson. Imaging 2015;41:1675–1681.

FROM THE DISCOVERIES of Lauterbur and Mansfield in the 1970s and the beginning of the clinical use of magnetic resonance imaging (MRI) in the early 1980s up to state-of-the-art-MRI today, with a variety of dedicated MRI applications such as interventional MRI or functional MRI, MRI has been and continues to be a success story. Today MRI is a widely accepted, integral part of clinical medicine, with broad availability and high diagnostic impact on almost any specialty in clinical medicine and the number of MRI examinations worldwide is still growing (1).

A major trend in MRI today is the application of higher and higher magnetic field strengths exceeding 3T to achieve higher signal-to-noise ratio (SNR), from which numerous imaging techniques benefit, eg, functional imaging, spectroscopy, or structural (high resolution) imaging. Although several technical challenges still have to be overcome, ultrahighfield MRI already offers several new possibilities in clinical imaging, especially in the field of (functional) neuroimaging, spectroscopy (2), and more recently also in musculoskeletal imaging (3,4).

The application of such high field strength revealed a number of formerly unknown acute, mild, and transient side effects in humans being exposed to 7T and above. These effects include neurobehavioral effects (5,6), effects in vital signs (7–10), and also sensory perceptions like vertigo, nausea, metallic taste, or the appearance of phosphenes (11,12). Several studies also investigated possible cognitive effects (7–10) and mainly denied them, although one work revealed "concentration problems" (13) and another work showed extremely small cognitive effects, but most likely due to statistical artifacts (14).

As there is a lack of reliable data on possible health effects of electromagnetic fields in general, there is a strong need for such studies, as recently pointed out by the European Parliament (15), the International

[1]Department of Radiology and Nuclear Medicine, Otto-von-Guericke University Magdeburg, Germany.
[2]Department of Biomedical Magnetic Resonance (BMMR), Division Experimental Physics, Faculty of Physics, Otto-von-Guericke University Magdeburg, Germany.
[3]Department of Economics, University of Zurich, Switzerland.
[4]Institute for Biometrics and Biomedical Informatics, Otto-von-Guericke University Magdeburg, Germany.
[5]Leibniz Institute for Neurobiology, Magdeburg, Germany.
*Address reprint requests to: B.F., Radiologie, Haus 60a, Leipziger Straβe 44, 39120 Magdeburg, Germany.
E-mail: bjoern.friebe@med.ovgu.de
Received April 22, 2014; Accepted July 21, 2014.
DOI 10.1002/jmri.24748
View this article online at wileyonlinelibrary.com.

Figure 1. Realistic mock scanner with head coil.

Commission on Non-Ionizing Radiation Protection (16), and the World Health Organization (17).

In the few present published studies, vertigo and other sensational side effects were reported to appear almost exclusively in subjects who were exposed to changing static magnetic fields while being moved on the patient table or while moving their head (13,18). These field strength-related sensations are of increasing relevance because of the rising number of MRI techniques where support staff are in close proximity to patients within a magnet, such as in MRI interventional procedures, where the performance of complicated tasks by the interventionist within the magnetic field is crucial.

The objective of this study was to determine the frequency and intensity of sensory perceptions caused by exposure to the static magnetic field of a 7T MRI scanner, compared to those in a realistic mock scanner with no magnetic field. Vital signs or neurobehavioral and/or cognitive effects were not assessed.

MATERIALS AND METHODS

Institutional Review Board approval was granted by the local Ethics Committee. All volunteers gave written informed consent prior to their participation in the study.

In all, 44 healthy subjects (26 female, 18 male, ages 23–32 years, mean 26.0) without a strong predisposition to vertigo were exposed to the static magnetic field of a 7T MRI scanner and subject reports were compared to a very similar exposure in a realistic mock scanner (MS) with no magnetic field (Fig. 1). Subjects were blinded to the magnetic field strength and did not know that one of the scanners was a mock scanner.

Each procedure was performed under identical conditions on the same day and in the same manner by one physician and one MR physicist. The subjects were identically instructed before each procedure to be mindful of potential sensations of discomfort while undergoing the procedure. Subjects were free to close their eyes or to leave them open during the procedure.

The procedure consisted of being moved into the isocenter of the bore of each system in a lying, head-first supine position, resting in the isocenter for 20 seconds and then being moved out of the bore again. The procedure was carried out in one machine first and then repeated identically in the other machine with randomized order and two different dedicated velocities (either "slow," ~0.1 m/s [20 sec to isocenter] or "fast," ~0.4 m/s [5 sec to isocenter]). Subjects were randomized to either the "fast" or the "slow" group.

The mock scanner was in a separate room in a building where 3T MRI measurements take place routinely. The room size and the lighting were comparable to other clinical MRI installations, while the scanner room of the 7T system was ~50% larger. Subjects changed their clothes in the regular change room of the real 3T MRI and then moved to the room of the mock system next door. The 7T system is in a separate building close to the mock scanner. Subjects were free to get dressed and undressed again between the two procedures, as there was a similar changing room at the 7T system. At the door of the room of the mock scanner the standard warning signs were installed (Fig. 2) and a 5 Gauss line surrounded the magnet. The mock scanner itself is an exhibition model with a fully functional patient table (Magnetom Avanto, Siemens, Germany) (Fig. 1). Head coils were used in each procedure to improve the realistic effect of the mock scanner. In addition, the acoustic noise background of the 7T including the sound of the compressor for magnet cooling was recorded and played at a realistic sound level via a high-quality surround sound speaker system hidden behind the cover of the mock scanner.

After each procedure the subjects were asked to fill out a "yes-or-no" questionnaire of 20 questions in total regarding potential sensory perceptions while undergoing the procedure, whereof 14 questions provided the opportunity of additional gradual scaling on a 10-point scale if positive.

Figure 2. Door of the room of the mock scanner with safety advice.

Table 1
At Least One Sensory Perception Reported in the 7T and/or in the MS

		At least one side effect in MS		
		Yes	No	Total
At least one side effect in 7T	yes	15	16	31
	No	4	9	13
Total		19	25	44

SPSS statistics software, v. 17 (Chicago, IL) was used for all data analyses. The occurrence of sensory perceptions was compared between 7T and MS using the McNemar test or paired Wilcoxon test in case of gradual scaling, both in the whole group of patients as stratified as "slow" ($n=22$) or "fast" ($n=22$). The modifying effect of the velocities on the occurrence of sensory perceptions was investigated in a generalized linear mixed model for the binary data and in a linear mixed model for the scales. In addition to the separate consideration of the 20 questions at an exploratory level, we studied the summary of all items (Was there at least one sensory perception?) and a selection of the five most important items according to the literature. All tests were two-sided and $P=0.05$ was considered significant.

RESULTS

Nine of 44 subjects (20.4%) did not report any sensory perceptions, ie, neither in the 7T scanner nor in the mock scanner. Of the group of the remaining 35 subjects (79.6%) who reported at least one sensory perception in the 7T and/or in the MS, 15 subjects reported them to appear in the 7T and in the MS (34.1%), 16 subjects reported them to appear only in the 7T (36.4%) and four subjects (9.1%) reported them to appear only in the MS (Table 1).

Thus, subject reports of at least one sensory perception of all 20 in the 7T alone are highly significant ($P<0.01$) more often than those reporting at least one sensory perception in the MS alone (16 vs. 4, $P=0.012$) (Table 1).

The absolute frequencies of all reported sensory perceptions, ie, perceptions observed in the 7T and in the MS and perceptions observed in the 7T or in the MS alone, are shown in Fig. 2. Apart from unspecific sensory perceptions such as "entering unpleasant," the most frequently observed specific sensory perception was "vertigo while entering the gantry," which was reported by 36.3% ($n=16$). Other frequent sensory perceptions were the appearance of phosphenes (reported by 18.2%), unsteady gait after exposure to the B_0 field (reported by 13.6%), thermal heat sensation during the procedure (reported by 13.6%), and dizziness (reported by 11, 4%) after the procedure. Nausea and metallic taste, which were reported in other studies, occurred in no case (Fig. 2).

Of all 20 possible sensory perceptions, five were found to appear significantly more often in the 7T than in the MS ("sensory perceptions due to magnetic field" [$P=0.039$], "vertigo moving in" [$P=<0.001$], "vertigo in isocenter" [$P=<0.001$], "unsteady gait after" [$P=0.031$], and "phosphenes" [$P=0.008$]) (Table 2).

Analyzing a subgroup of five sensory perceptions ("Selection 5") that were reported to be relevant in the literature ("vertigo moving in," "appearance of phosphenes," "unsteady gait after exposure," "thermal heat sensation," and "dizziness"), the number of subjects in this subgroup reporting at least one of these sensory perceptions in the 7T alone was highly significantly greater than those reporting at least one of the criteria in the MS ($P=<0.001$; Table 2). Additionally, a percentage accordance between the reported side effects of the 7T and the MS was calculated, which showed the percentage of subjects who did report or did not report the same sensory perception in both the mock scanner and the 7 T scanner. It ranged from 52.3% to 97.7% with an average of 83.4% (median 87.4%; Table 2).

As half of the subjects underwent the procedure with "fast" motion and the other half of the subjects with "slow" motion, significances were also calculated separately for these subgroups. Concerning the individual sensory perceptions in the "fast" group only "vertigo moving in" was shown to appear significantly more often in the 7T ($P=0.031$; Table 2). In the "slow" group three sensory perceptions were shown to appear more often in the 7T ("sensory perceptions magnetic field" [$P=0.013$], "vertigo moving in" [$P=0.004$], and "vertigo in isocenter" [$P=0.004$]) (Table 2).

Table 2
McNemar Test

Sensation	McNemar	Total Accordance	Slow McNemar	Fast McNemar
Selection 5	<0.001	52.3	0.001	0.021
Total	0.012	54.5	0.004	0.549
Acc. heart beat	0.727	81.8	1.000	0.375
Entering unpleasant	0.219	86.4	0.250	1.000
Moving out unpleasant	1.000	93.2	1.000	1.000
Noticing MF	0.063	88.4	0.250	0.500
Sensory perceptions MF	0.039	79.5	0.013	0.375
Headache	1.000	93.2	1.000	0.500
Vertigo moving in	<0.001	65.9	0.004	0.031
Vertigo in isocenter	<0.001	68.2	0.004	0.063
Vertigo moving out	0.250	93.2	1.000	0.500
Vertigo after	0.453	84.1	1.000	0.250
Sweating	0.250	93.2	0.500	1.000
Unsteady gait after	0.031	86.4	0.063	1.000
Phosphenes	0.008	81.8	0.125	0.125
Thermal heat	1.000	88.6	1.000	1.000
Cold	1.000	95.5	1.000	1.000
Fatigue	1.000	97.7	1.000	1.000
Dizziness	0.625	90.9	0.500	1.000
Restlessness	1.000	93.2	0.500	1.000

Calculated *P*-values of all reported sensory perceptions for the entire group, for the "slow" group, and the "fast" group with additional percentage accordance. In the case of a significant *P*-value, the effect was always shown to appear more frequently in the 7T.

Table 3
Wilcoxon Test

Sensation	Wilcoxon Total	Wilcoxon Slow	Wilcoxon Fast	Linear mixed model: Velocity	Linear mixed model: Machine	Linear mixed model: Velocity*machine
Selection 5	<0.001	<0.001	0.016	0.069	0.001	0.074
Total	<0.001	<0.001	0.045	0.174	0.001	0.048
Entering unpleasant	0.007	0.012	0.375	0.117	0.008	0.382
Moving out unpleasant	0.250	0.313	1.000	0.231	0.181	0.337
Noticing MF	0.063	0.250	0.500	0.669	0.027	0.669
Headache	1.000	0.500	0.500	0.531	1.000	0.061
Vertigo moving in	<0.001	0.002	0.031	0.474	<0.001	0.555
Vertigo in isocenter	<0.001	0.002	0.063	0.148	<0.001	0.159
Vertigo moving out	0.313	0.500	0.500	0.333	0.216	0.593
Vertigo after	0.234	1.000	0.250	1.000	0.162	0.293
Sweating	0.250	0.500	1.000	0.343	0.157	0.343
Thermal heat	0.688	0.500	1.000	0.192	0.428	0.269
Cold	1.000	1.000	1.000	1.000	1.000	0.165
Fatigue	1.000	1.000	1.000	0.323	0.323	0.323
Dizziness	0.500	0.500	1.000	0.131	0.274	0.161
Restlessness	0.750	0.500	1.000	0.411	0.411	0.104

Calculated *P*-values of all reported sensory perceptions for the entire group, for the “slow” group and the “fast” group. In the case of significant *P*-value, the effect was always shown to appear stronger in the 7T. The mixed linear model analysis showed a significant influence of the machine (ie, 7T) and a significant influence of the velocity in combination with the particular machine (ie, significantly greater difference in the 7T). A significant influence of the velocity alone could not be shown. “Selection 5” and “Total” here presents the number of items with positive sensory perception.

The subgroup of the selection of the five relevant sensory perceptions mentioned above ("Selection 5") was significant in both the "fast" and the "slow" group, in the "slow" subgroup even highly significant ($P = 0.001$). Concerning the entire group (at least one reported sensory perception of all 20, "Total") only in the "slow" group the sensory perceptions were shown to appear significantly more often in the 7T than in the mock scanner ($P = 0.004$; Table 2).

Furthermore, a mixed linear model analysis was calculated to show a potential modifying effect of the velocity on the frequency of the appearance of the sensory perceptions reported. However, no significance could be shown here.

As 14 out of 20 questions provided the additional possibility of gradual scaling on a 0–10 scale, Wilcoxon tests were also applied (Table 3). Similar to the McNemar test, the same sensory perceptions that were shown to appear significantly more often ("vertigo while moving in" and "vertigo in isocenter") were shown to appear significantly stronger in the 7T in the Wilcoxon test. Additionally, in the Wilcoxon test "entering unpleasant" was shown to be significantly stronger in the 7T, which did not appear significantly more often in the McNemar test.

Furthermore, the grade of the reported sensory perceptions in the group of subjects who reported at least one sensory perception of all 20 in the 7T was significantly stronger than that of the group in the mock scanner ($P = < 0.001$). This was also the case in the subgroup "Selection 5" ($P = < 0.001$).

Concerning the individual sensory perceptions in the "fast" group only, "vertigo moving in" was shown to appear significantly stronger in the 7T ($P = 0.031$; Table 3), as well as to appear more often in the 7T in the McNemar test (Table 2).

In the "slow" group, three sensory perceptions were shown to appear stronger in the 7T ("entering unpleasant" [$P = 0.012$], "vertigo moving in" [$P = 0.002$], and "vertigo in isocenter" [$P = 0.002$]) (Table 3).

The entire group (at least one sensory perception of all 20) was shown to reveal significantly stronger effects in the 7T than in the mock scanner in both the "fast" and the "slow" group; in the "slow" group highly significantly stronger ($P = 0.045$ in the "fast" group and $P = < 0.001$ in the "slow" group). This was also the case in the "Selection 5" group ($P = 0.016$ in the "fast" group and $P = < 0.001$ in the "slow" group).

In the mixed linear model analysis, all significant differences were shown to be stronger in the 7T ("machine"; Table 3). A separate influence of the velocity alone could not be shown. However, an interaction was shown in the velocity and the machine effect (velocity*machine), ie, the difference between the 7T and the MS was significantly greater in the "slow" group than in the "fast" group (Table 3, $P = 0.048$).

The absolute grades of the reported sensory perceptions ranged from 0 to 8 in the 7T with an average of 1.82 (median 2.0) and from 1 to 6 in the MS with an average of 1.68 (median 1.0). In Fig. 4 the strength of the reported sensory perceptions is categorized into "light," "medium," and "strong."

DISCUSSION

With the introduction of higher and ultrahighfield strengths in MRI, previously irrelevant side effects of the B_0 field were reported. The sensory perception that was observed most frequently in the literature is a light vertigo while entering the gantry or during movements of the subjects themselves (9,19–21). The physical mechanism that underlies this interaction is

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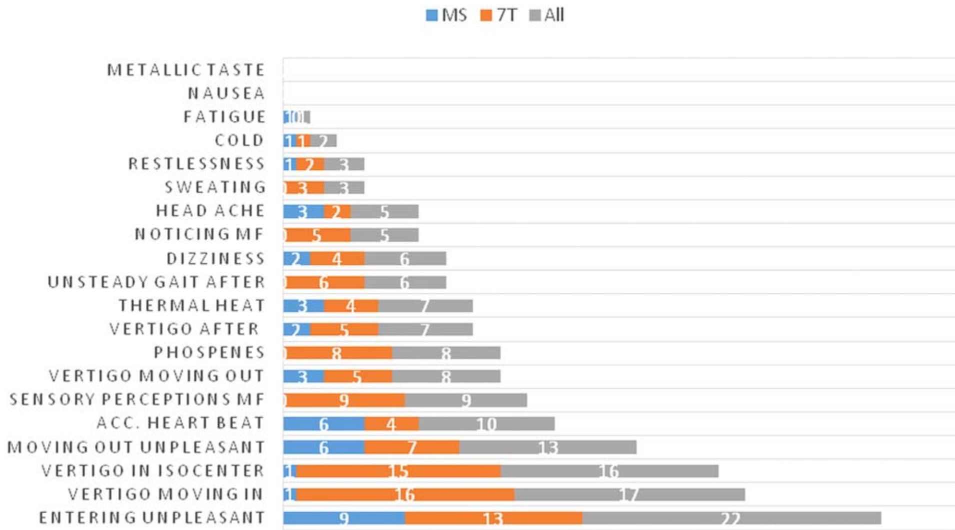

Figure 3. Absolute frequencies of all reported sensory perceptions in number of subjects. Metallic taste and nausea occurred in no cases.

magnetoinduction, ie, the induction of electric currents or fields and the electromagnetic interaction of moving electrolytes in moving subjects in a magnetic field (22). These inducted electric currents can lead to action on vestibular hair cells and/or magnetic susceptibility differences between vestibular organs and the surrounding fluid, likely causing the reported sensation of light vertigo (22). Magnetoinduction is field-dependent and according to theoretical calculations becomes relevant in humans in magnetic fields of and above 2T (23).

A limitation of most studies investigating sensory perceptions of highfield MRI published until the present is the lack of a control group. This can be achieved by using a mock scanner with no magnetic field, which was implemented for the first time by Atkinson et al (9) in a study investigating the influence of vital signs or cognitive ability at sodium MRI, and later in a study by Heinrich et al (10) with a focus on cognitive effects. In our study we used a mock scanner as a control to investigate sensory perceptions. By using such a mock scanner we show for the first time that the appearance of known sensory perceptions of subjects undergoing ultrahighfield MRI, eg, vertigo or metallic taste, is not only due to the known physical mechanisms of interaction with the static magnetic field but also due to other factors, as these sensory perceptions also appeared in the mock scanner with no magnetic field. In our study population 19 subjects (43.2%) reported experiencing sensory perceptions in the MS, which are assumed to be B_0 field-related. This group even contained a subgroup of four subjects (9%) who reported such sensations to appear only in the MS (Table 1). Referred possible explanations for these findings are psychological effects that may be elicited by individual expectations of the procedure or the surroundings of the procedure. This includes the detailed description of possible side effects in the subject informed consent form. It has to be assumed that such effects contribute significantly to the incidence of sensations reported in magnetic field exposure studies that rely on self-reporting. Also, the list of possible side effects in a questionnaire may be suggestive and influence the results. A previous study (24) pointed in a similar direction, as it was shown that the incidence of reported effects due to high magnetic field exposure can be reduced by antimotion sickness drugs but also by placebo. As the procedures at 0T and 7T were carried out on the same day, another explanation of the reported sensory perceptions in the mock scanner could be the occurrence of extended sensations or an interaction with short-term memory. We tried to reduce such effects by randomized exposition order. No difference between the subjects who first experienced 0T vs. 7T was detected.

The fact that 9 out of 44 subjects (20.4%) did not report any side effects, ie, either in the 7T scanner or in the MS, shows the strong individual predisposition and inconstant appearance of the perceptions, as shown in previous studies (7,12,18). Of these nine subjects, three had never had any MRI examination before.

Consistent with previous reports (9,19–21), vertigo while entering the gantry was the most frequently observed sensory perception—apart from unspecific perceptions of our questionnaire such as "entering unpleasant." Although consistent with previous reports, the data reinforce this finding by using a mock scanner as a control, which has been used only to a very limited extent in previous studies until today. Other frequent sensory perceptions were the appearance of phosphenes (reported by 18.2%), unsteady gait after exposure to the B_0 field (reported by 13.6%), thermal heat sensation during the procedure (reported by 13.6%), and dizziness after the procedure (reported by 11.4%). Some sensory perceptions that were described in previous studies were not reported in our study, ie, nausea and metallic taste (Fig. 3). The degree of the reported sensory perceptions was mainly described as light to moderate, with a slightly lower subjective rating in the MS, which may have been expected.

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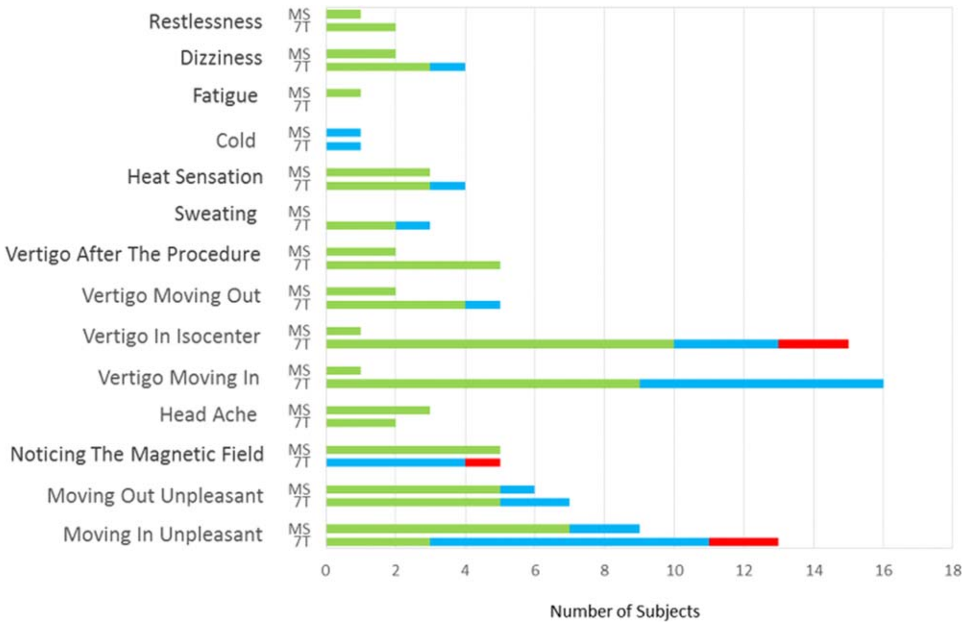

Figure 4. Absolute grades of reported sensory perceptions in the 7T and in the mock scanner (MS). The grade of the sensory perception could be rated from 1 (very weak) to 10 (very strong). For a better overview, subject reports were divided into mild (green), medium (blue), and strong (red).

As our questionnaire also contained some unspecific and redundant questions, we formed a group of criteria that were described as common and relevant, as mentioned above ("Selection 5"). Here, a strong correlation with the field exposure was shown.

It is known that most sensory perceptions are reported to appear almost only in subjects who were exposed to magnetic fields with a moving table or while moving their head (13,18,19). This is of special relevance for new MRI techniques such as interventional MRI, in which the interventionist has to perform complicated tasks within the magnetic field. In this context, we additionally investigated a potential influence of the velocity of the table motion. Some studies revealed results that suggest that entering the patient into the bore of the magnet with a slow velocity reduces vertigo, which corresponds to the theoretical explanations of vertigo. De Vocht et al (13) found that almost all complaints of employees working in the stray field of 1.0 and 1.5T MRIs were more frequently reported while moving with a "fast" velocity rather than with a "slow" velocity. Also, Theysohn et al (19) reported that in 102 subjects who underwent 7T MRI, vertigo was rated significantly worse during table movement compared to a stationary table position. In contrast to these findings, our study population showed a trend to more reported sensory perceptions in the "slow" group, although in these two studies—as well as in our study—sensory perceptions were reported also at a stationary table position. As a matter of fact, in the mixed model analysis there was a significant influence of the velocity in combination with the field exposure. In particular, the difference between the rate of reported sensory perceptions at 7T and in the MS was significantly greater in the "slow" group than in the "fast" group. As mentioned above, one of the most likely theories of the emergence of vertigo in highfield strengths is that currents inducted by magnetoinduction during movement are acting on vestibular hair cells. It may be assumed that the strength of the perceived effects is a function of the main magnetic field strength, the change in the magnetic field strength (dB/dt), and the exposure time, ie, duration of table motion (25). The relation might be nonlinear, leading to the hypothesis that the shorter exposition time of the "fast" group (5 vs. 20 sec exposure to changing magnetic field) may dominate the high induction strength and lead to a lower rate of sensory perceptions in this group.

It is known that any linear or rotational acceleration of the head (consequently also table movement even without magnetic field) can cause vertigo, as it can deflect the cupula within the semicircular canals (26,27). This effect, however, is expected to increase with acceleration, ie, the fast table condition. Additionally, table movement (or movement in general) can have psychological effects. However, psychological effects like short-term memory or extended sensation are very subjective and difficult to separate.

Further studies are required to separate the possible mechanisms. According to the results, it might be appropriate to move patients into the bore with a fast motion to avoid vertigo, as in the mixed model analysis there was a significant influence of the velocity, although in combination with the field exposure, as mentioned above. A separate influence of the velocity alone (ie, in the 7T and in the MS separately) could not be shown, which might be due to the moderate sample size as each subject was randomized to either the "fast" or the "slow" group.

In conclusion, light, acute, and transient sensory perceptions can occur in subjects undergoing ultrahigh-field MRI. These effects are field-dependent and occur mainly during table movement or potential movement of the patient, consistent with the assumption of the main mechanism of its emergence, magnetoinduction. The sensory perceptions are, however, largely inconsistent between subjects and do not appear in all subjects. These findings are consistent with previous studies. The most frequent sensory perception is light vertigo while entering the magnet bore. In contradiction to previous studies, this might be avoided in future studies by moving the patient in with a relatively fast velocity in order to reduce the time of exposure to the changing field. As some subjects reported identical or even more severe sensory perceptions in a mock scanner, we presume that the emergence of these sensory perceptions is not only due to magnetoinduction but also due to possible psychological effects that may be elicited by individual expectations induced by the subject information. Such bias effects should be considered when the individual perceptions due to static magnetic fields are assessed by self-reporting.

REFERENCES

1. OECD. OECD Health Data. 2013, OECD.
2. Novak V, Christoforidis G. Clinical promise: clinical imaging at ultra high field. In: Robitaille PM, Berliner LJ, editors. Ultra high field magnetic resonance imaging, 1st ed. Berlin: Springer; 2006. p 411–437.
3. Trattnig S, Zbyn S, Schmitt B, et al. Advanced MR methods at ultra-high field (7 Tesla) for clinical musculoskeletal applications. Eur Radiol 2012;22:2338–2346.
4. Krug R, Stehling C, Kelley DA, et al. Imaging of the musculoskeletal system in vivo using ultra-high field magnetic resonance at 7 T. Invest Radiol 2009;44:613–618.
5. de Vocht F, van-Wendel-de-Joode B, Engels H, et al. Neurobehavioral effects among subjects exposed to high static and gradient magnetic fields from a 1.5 Tesla magnetic resonance imaging system–a case-crossover pilot study. Magn Reson Med 2003;50:670–674.
6. de Vocht F, Stevens T, van Wendel-de-Joode B, et al. Acute neurobehavioral effects of exposure to static magnetic fields: analyses of exposure-response relations. J Magn Reson Imaging 2006;23: 291–297.
7. Kangarlu A, Burgess RE, Zhu H, et al. Cognitive, cardiac, and physiological safety studies in ultra high field magnetic resonance imaging. Magn Reson Imaging 1999;17:1407–1416.
8. Chakeres DW, Kangarlu A, Boudoulas H, et al. Effect of static magnetic field exposure of up to 8 Tesla on sequential human vital sign measurements. J Magn Reson Imaging 2003;18:346–352.
9. Atkinson IC, Renteria L, Burd H, et al. Safety of human MRI at static fields above the FDA 8 T guideline: sodium imaging at 9.4 T does not affect vital signs or cognitive ability. J Magn Reson Imaging 2007;26:1222–1227.
10. Heinrich A, Szostek A, Meyer P, et al. Cognition and sensation in very high static magnetic fields: a randomized case-crossover study with different field strengths. Radiology 2013;266:236–245.
11. Schenck JF. Health and physiological effects of human exposure to whole-body four-Tesla magnetic fields during MRI. Ann N Y Acad Sci 1992;649:285–301.
12. Schenck JF, Dumoulin CL, Redington RW, et al. Human exposure to 4.0-Tesla magnetic fields in a whole-body scanner. Med Phys 1992;19:1089–1098.
13. de Vocht F, van Drooge H, Engels H, et al. Exposure, health complaints and cognitive performance among employees of an MRI scanners manufacturing department. J Magn Reson Imaging 2006;23:197–204.
14. Chakeres DW, Bornstein R, Kangarlu A. Randomized comparison of cognitive function in humans at 0 and 8 Tesla. J Magn Reson Imaging 2003;18:342–345.
15. Mattsson MO AA, Bridges J Norppa H, Schutz J. European Parliament and the Council. Research needs and methodology to address the remaining knowledge gaps on the potential health effects of EMF. 2013.
16. International Commission on Non-Ionizing Radiation. Guidelines on limits of exposure to static magnetic fields. Health Phys 2009; 96:504–514.
17. WHO. Environmental Health Criteria 232 static fields. 2006.
18. Schenck JF. Safety of strong, static magnetic fields. J Magn Reson Imaging 2000;12:2–19.
19. Theysohn JM, Maderwald S, Kraff O, et al. Subjective acceptance of 7 Tesla MRI for human imaging. MAGMA 2008;21:63–72.
20. Heilmaier C, Theysohn JM, Maderwald S, et al. A large-scale study on subjective perception of discomfort during 7 and 1.5 T MRI examinations. Bioelectromagnetics 2011;32:610–619.
21. Chakeres DW, de Vocht F. Static magnetic field effects on human subjects related to magnetic resonance imaging systems. Prog Biophys Mol Biol 2005;87:255–265.
22. Glover PM, Cavin I, Qian W, et al. Magnetic-field-induced vertigo: a theoretical and experimental investigation. Bioelectromagnetics 2007;28:349–361.
23. Crozier S, Liu F. Numerical evaluation of the fields induced by body motion in or near high-field MRI scanners. Prog Biophys Mol Biol 2005;87:267–278.
24. Thormann M, Amthauer H, Adolf D, et al. Efficacy of diphenhydramine in the prevention of vertigo and nausea at 7 T MRI. Eur J Radiol 2013;82:768–772.
25. Cavin ID, Glover PM, Bowtell RW, et al. Thresholds for perceiving metallic taste at high magnetic field. J Magn Reson Imaging 2007;26:1357–1361.
26. Oman CM, Young LR. The physiological range of pressure difference and cupula deflections in the human semicircular canal. Theoretical considerations. Acta Otolaryngol 1972;74:324–331.
27. Oman CM, Marcus EN, Curthoys IS. The influence of semicircular canal morphology on endolymph flow dynamics. An anatomically descriptive mathematical model. Acta Otolaryngol 1987;103: 1–13.