



Specific Absorption Rate and Specific Energy Dose: Comparison of 1.5-T versus 3.0-T Fetal MRI

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Background: MRI performed at 3.0 T offers greater signal-to-noise ratio and better spatial resolution than does MRI performed at 1.5 T; however, for fetal MRI, there are concerns about the potential for greater radiofrequency energy administered to the fetus at 3.0-T MRI.

Purpose: To compare the specific absorption rate (SAR) and specific energy dose (SED) of fetal MRI at 1.5 and 3.0 T.

Materials and Methods: In this retrospective study, all fetal MRI examinations performed with 1.5- and 3.0-T scanners at one institution between July 2012 and October 2016 were evaluated. Two-dimensional (2D) and three-dimensional (3D) steady-state free precession (SSFP), single-shot fast spin-echo, 2D and 3D T1-weighted spoiled gradient-echo (SPGR), and echo-planar imaging sequences were performed. SAR, SED, accumulated SED, and acquisition time were retrieved from the Digital Imaging and Communications in Medicine header. Data are presented as mean \pm standard deviation. Two one-sided tests with equivalence bounds of 0.5 (Cohen *d* effect size) were performed, with statistical equivalence considered at $P < .05$.

Results: A total of 2952 pregnant women were evaluated. Mean maternal age was 30 years \pm 6 (age range, 12–49 years), mean gestational age was 24 weeks \pm 6 (range, 17–40 weeks). A total of 3247 fetal MRI scans were included, with 2784 (86%) obtained at 1.5 T and 463 (14%) obtained at 3.0 T. In total, 93764 sequences were performed, with 81535 (87%) performed at 1.5 T and 12229 (13%) performed at 3.0 T. When comparing 1.5- with 3.0-T MRI sequences, mean SAR (1.09 W/kg \pm 0.69 vs 1.14 W/kg \pm 0.61), mean SED (33 J/kg \pm 27 vs 38 J/kg \pm 26), and mean accumulated SED (965 J/kg \pm 408 vs 996 J/kg \pm 366, $P < .001$) were equivalent.

Conclusion: Fetal 1.5- and 3.0-T MRI examinations were found to have equivalent energy metrics in most cases. The 3.0-T sequences, such as two-dimensional T1-weighted spoiled gradient-echo and three-dimensional steady-state free precession, may require modification to keep the energy delivered to the patient as low as possible.

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MRI performed at 3.0 T has advantages when compared with MRI performed at 1.5 T (1). The higher field strength results in higher signal-to-noise ratio and spatial resolution. However, the transition from 1.5 to 3.0 T in fetal MRI brings safety concerns associated with the higher magnetic field strength and radiofrequency power (2). Each excitation and refocusing radiofrequency pulse of an MRI sequence deposits energy into the individual being scanned, which is converted into heat. The rate of energy deposition depends on the amplitude of the radiofrequency pulse. When a transition from 1.5 to 3.0 T is made and all other factors are kept constant, energy deposition may quadruple, leading to undesired heating (3).

Heating is a concern in fetal MRI; temperature increases experienced by the gravid patient for relatively prolonged periods may be teratogenic (4). There is no direct way to measure fetal tissue heating, so tissue power deposition is quantified by measuring the specific absorption rate

(SAR). This energy metric is defined as the radiofrequency power absorbed over time per unit of mass of an object (measured in Watts per kilogram of body weight) (5–8). It is based on the approximate modeling of the individual's body—in this case, the gravid patient—and depends mainly on the field strength and radiofrequency power.

The Food and Drug Administration sets strict limits on individual exposure to a certain power deposition, with an upward SAR limit of 4 W/kg averaged over 15 minutes for the maternal whole body (9,10). There is no set limit for the fetus (9,11). According to the International Electrotechnical Commission (IEC), the upper SAR limit under the normal operating mode is 2 W/kg averaged over 6 minutes (8).

The specific energy dose (SED) is the cumulative absorbed dose (measured in Joules per kilogram of body weight). It represents the total accumulated energy deposited in the individual being scanned rather than an average over time (12). This value can be calculated per sequence,

Abbreviations

CNS = central nervous system, EPI = echo-planar imaging, IEC = International Electrotechnical Commission, SAR = specific absorption rate, SED = specific energy dose, SSFP = steady-state free precession, SSTSE = single-shot turbo spin echo, SPGR = spoiled gradient echo, 3D = three-dimensional, 2D = two-dimensional, TOST = two one-sided test

Summary

Fetal MRI can be performed and optimized to deliver an equivalent amount of energy at 3.0 and 1.5 T.

Key Results

- A total of 3247 fetal MRI examinations (mean gestational age, 24 weeks) were compared for radiofrequency energy administration at 1.5 and 3.0 T.
- When comparing optimized fetal MRI at 1.5 T with that at 3.0 T, the mean specific absorption rate (1.09 vs 1.14 W/kg), mean specific energy dose (33 vs 38 J/kg), and mean accumulated specific energy dose (965 vs 996 J/kg), respectively, were statistically equivalent.

but it is more commonly used to estimate the total energy delivered throughout the entire MRI examination. The IEC has set an SED limit of less than 14000 J/kg per MRI examination on a first-level controlled MRI mode (8).

There may be clinical concerns when using 3.0-T MRI scanners as compared with 1.5-T MRI scanners because of the potential for increased SAR and SED at 3.0 T (3,13). Previous studies showed that radiofrequency energy deposition could be reduced by modifying MRI parameters in well-known sequences (14,15). The purpose of this study was to compare and evaluate the equivalence of SAR and SED of fetal MRI obtained at 1.5 and 3.0 T.

Materials and Methods

This was a retrospective study approved by the institutional review board at the Children's Hospital of Philadelphia and performed in compliance with the Health Insurance Portability and Accountability Act. The requirements for written informed consent were waived.

Patient Sample

A computer search of the radiology department's database between July 2012 (when 3.0-T fetal imaging was introduced at our tertiary pediatric institution) and October 2016 was performed and included patients older than 18 years who had undergone fetal MRI in a consecutive fashion. Patients with incomplete clinical information or those in whom MRI was prematurely aborted were excluded. MRI scanner parameters were retrieved from the Digital Imaging and Communications in Medicine headers. Demographic information, including maternal age, gestational age, and weight, was collected from the medical record.

MRI Protocol

Fetal MRI was performed with one 1.5-T scanner (Magnetom Avanto; Siemens Healthcare, Erlangen, Germany [$n = 2784$]) and three different 3.0-T scanners (Skyra [$n = 407$], Verio [$n =$

28], and Prisma [$n = 28$]; Siemens Healthcare). The sequences performed included two-dimensional (2D), three-dimensional (3D), and cine steady-state free precession (SSFP); single-shot turbo spin-echo (SSTSE); 2D and 3D T1-weighted spoiled gradient-echo (SPGR); and echo-planar imaging (EPI). For the 1.5-T MRI examinations, the imaging parameters for the key sequences were as follows: SSFP (repetition time msec/echo time msec, 4.05/1.65; flip angle, 70°), SSTSE (1100/76; flip angle, 180°), T1-weighted SPGR (202/4.76; flip angle, 60°), and EPI (5200/75; flip angle, 90°).

For the 3.0-T MRI examinations, the imaging parameters for the key sequences were as follows: SSFP (4.66/1.93; flip angle, 90°), SSTSE (1100/76; flip angle, 180°), T1-weighted SPGR (180/4.76; flip angle, 60°), and EPI (4800/46; flip angle, 90°). The field of view (range, 280–300 mm) and section thickness (range, 3–10 mm) remained constant for these sequences for both 1.5- and 3.0-T scanners. Scanner parameters for each sequence according to field strength and protocol are summarized in Table E1 (online). The number of acquisitions was partly determined by the radiologist during each MRI examination.

At our institution, every fetal MRI examination follows a protocol according to abnormality and is then categorized as a fetal central nervous system (CNS) (brain, head, neck, or spine) or body (all structures not included in the brain, head, neck, or spine) examination. As an example, a fetal CNS protocol is indicated to evaluate patients with myelomeningocele or ventriculomegaly, whereas a fetal body protocol is indicated to evaluate patients with congenital diaphragmatic hernia. CNS protocols are heavily based on SSFP sequences, whereas body protocols usually employ a combination of the sequences delineated previously, with an emphasis on SSFP and SSTSE imaging.

SAR and SED

The SAR and acquisition time values were retrieved from the Digital Imaging and Communications in Medicine header. The SED, which reflects the sum of energy absorbed by the patient over the course of MRI, was calculated as SAR multiplied by the sequence acquisition time (in seconds).

Statistical Analysis

Statistical analyses were performed (J.C.E., C.A.B; 15 and 3 years of experience, respectively) using SPSS (version 25; IBM, Armonk, NY) and R (version 3.5.2; R Foundation for Statistical Computing, Vienna, Austria) software. Descriptive information indicated demographic characteristics for each group. Continuous variables are presented as mean \pm standard deviation, and categorical variables are presented as percentages and counts. The independent t test was used to evaluate difference in demographic and scanner information between 1.5 and 3.0-T groups.

Raw differences and effect sizes were reported, with effect size calculated by using the Cohen d formula (mean difference between groups divided by pooled standard deviations). A Cohen d effect size was classified as minimal at less than 0.20, as small between 0.20 and 0.49, as medium between 0.50 and 0.79, and as large at 0.80 or greater (16,17).

Equivalence testing between 1.5 and 3.0 T in terms of SAR and SED was performed by using the Schuirmann method of

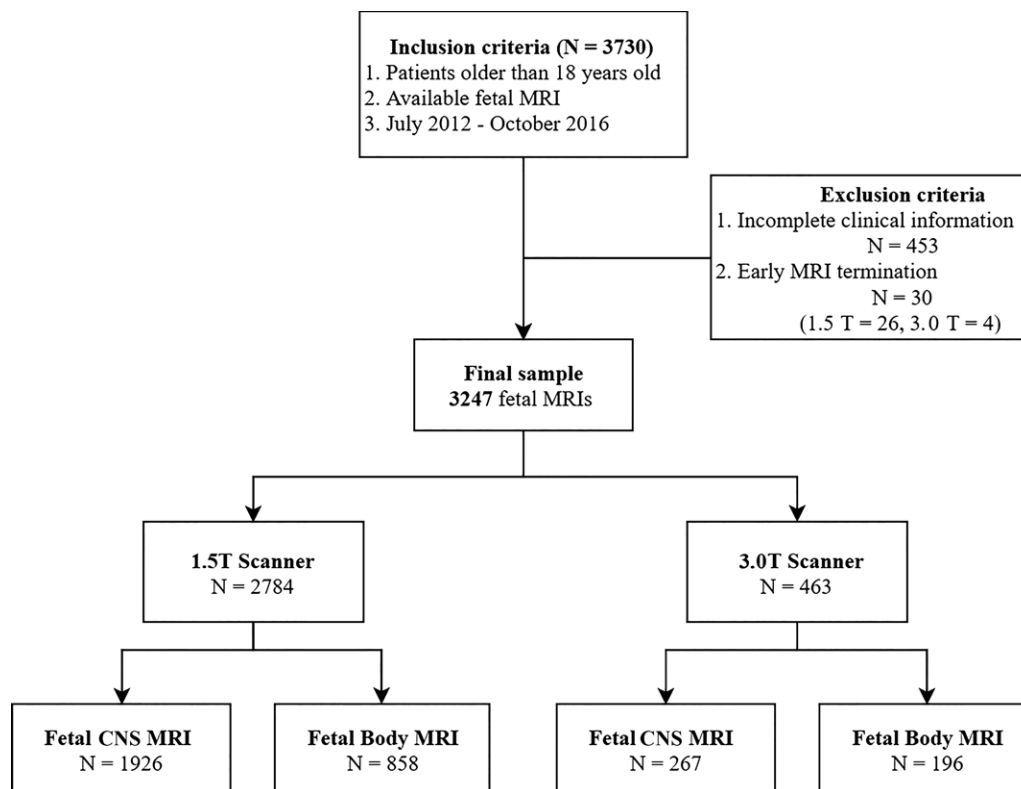


Figure 1: Flowchart shows the number of patients who fulfilled the inclusion criteria and the total sample used for analysis per field strength and MRI protocol.

Table 1: Demographic Information according to Field Strength

Variable	1.5 T (n = 2784)		3.0 T (n = 463)	
	Mean*	Range	Mean*	Range
Maternal age (y)	30 ± 6	12–49	29 ± 6	12–46
Gestational age (wk)	24 ± 4	17–40	29 ± 4	17–39
Weight (kg)	78 ± 18	38–241	81 ± 26	48–284
Total acquisition time (sec)	734 ± 285	261–2114	797 ± 288	278–2176
No. of sequences	29 ± 10	15–95	26 ± 9	15–70

Note.—All variables were significantly different ($P < .001$) between the 1.5- and 3.0-T groups with an independent-sample t test.

* Data are mean ± standard deviation.

two one-sided test (TOST) with an equivalence margin (Cohen d effect size) of 0.50; adjusted equivalence bounds were calculated per analysis based on the equivalence margin (18,19). If the mean difference and its 95% confidence interval fell within the 95% equivalence bounds, the values were considered equivalent.

Two P values were obtained per TOST (one per equivalent bound), but only the largest P value was reported. A Cohen d effect size of 0.50 was selected for the TOST equivalence bounds, as this cutoff ignores very small effects that are clinically unimportant but still allows medium-sized effects to be captured. Statistical equivalence was defined as $P < .05$ in the context of a TOST.

Sequences were classified according to whether they reached an SAR greater than 2 W/kg, as this is the upper limit set by the

IEC for normal operating mode. The IEC cutoff was selected given that all our scanners are programmed to not run a sequence that yields an SAR greater than 4 W/kg, as required by the Food and Drug Administration.

The percentage of maximum SAR (2 W/kg for a normal operating mode) was calculated at 1.5 and 3.0 T (mean SAR divided by two). The percentage difference with respect to the 2 W/kg cutoff was calculated by subtracting the percentage of maximum SAR at 1.5 T from that at 3.0 T. The percentage of maximum accumulated SED and percentage difference were calculated by using the 14000 J/kg cutoff established by the IEC. The χ^2 test was used to evaluate the prevalence of sequences with a SAR greater than 2 W/kg at 1.5 and 3.0 T. Two-tailed $P < .05$ was considered indicative of a significant difference for the χ^2 tests.

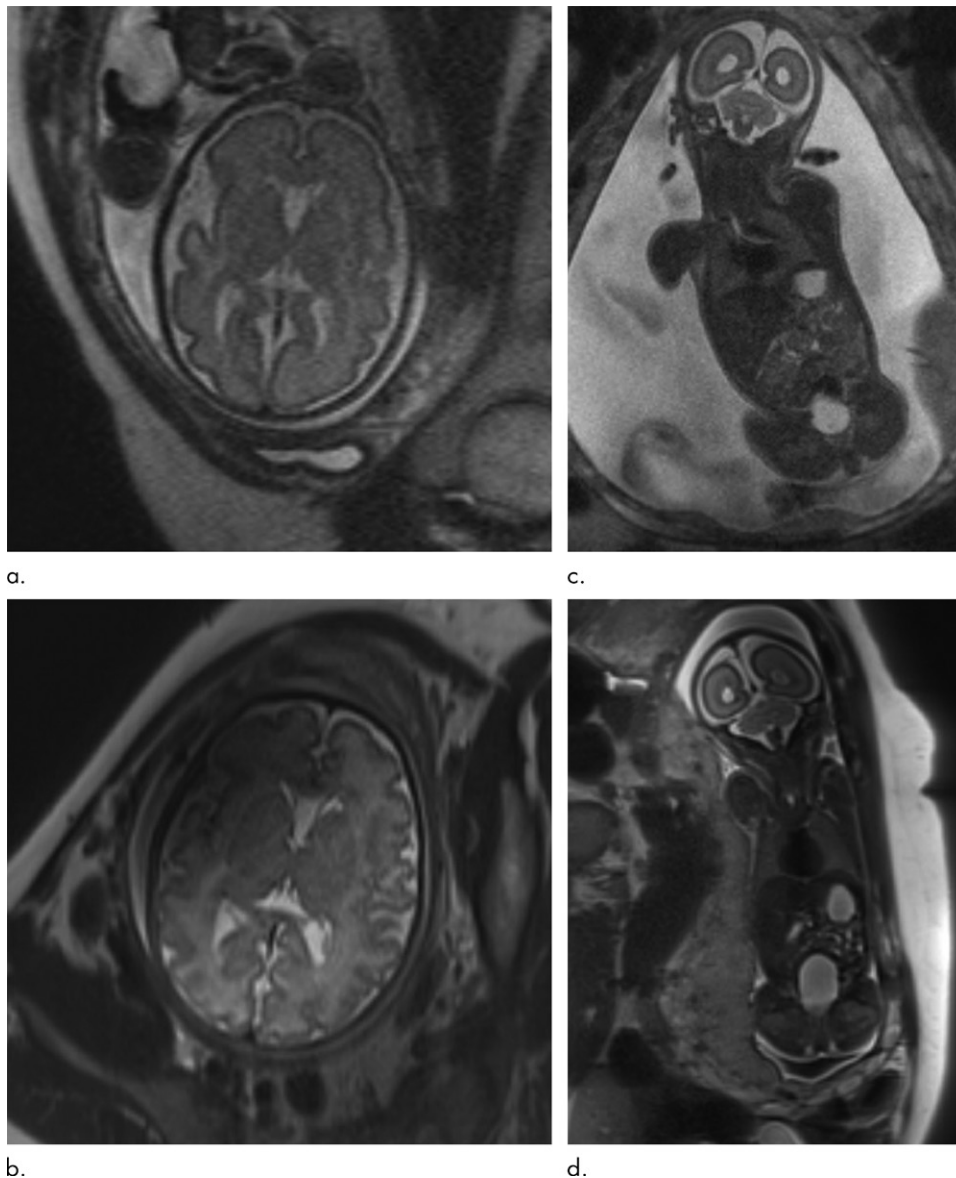


Figure 2: Images comparing the subjective image quality of different fetal MRI protocols at 1.5 and 3.0 T. **(a, b)** Fetal central nervous system MRI scans of the same fetus in a 29-year-old woman obtained at 23 **(a)** and 33 **(b)** weeks of gestation using single-shot turbo spin-echo sequences. The image quality is considerably better at 3.0 T (specific absorption rate [SAR], 1.54 W/kg; specific energy dose [SED], 54 J/kg) **(b)** than at 1.5 T (SAR, 1.53 W/kg; SED, 55 J/kg) **(a)**. **(c, d)** Fetal body MRI scans of two fetuses at 23 weeks gestation in two 30-year-old patients obtained using 1.5 T (SAR, 1.65 W/kg; SED, 43 J/kg) **(c)** and 3.0 T (SAR, 1.54 W/kg; SED, 45 J/kg) **(d)** with single-shot turbo spin-echo sequences. Both acquisitions have similar SAR and SED; however, the image quality is considerably better at 3.0 T than at 1.5 T.

Results

Study Population

Between July 2012 and October 2016, a total of 3730 fetal MRI examinations were performed in 3225 patients at our institution. A total of 483 MRI examinations were excluded because of incomplete clinical information or early MRI termination. From the remaining 2952 patients, 3247 fetal MRI examinations were included; 2784 (86%) were obtained with the 1.5-T scanner and 463 (14%) were obtained with a 3.0-T scanner (Fig 1). In total, 93764 sequences were retrieved for statistical analysis; 81 535 (87%) were performed with a 1.5-T

scanner, and 12229 (13%) were performed with a 3.0-T scanner. Among the 2952 pregnant women included in our study, mean maternal age was 30 years \pm 6 (range, 12–49 years), mean gestational age was 24 weeks \pm 6 (range, 17–40 weeks), and mean maternal weight was 78 kg \pm 19 (range, 38.2–284.0 kg) (Table 1).

Sequence Evaluation

The mean number of sequences (29 sequences \pm 10 vs 26 sequences \pm 9) and total acquisition time (734 vs 797 seconds) performed per MRI examination at 1.5 T were significantly equivalent compared with those at 3.0 T (TOST, $P <$

Table 2: SAR and SED Obtained with 1.5- and 3.0-T Scanners and Different MRI Protocols

Parameter	1.5 T			3.0 T			Cohen <i>d</i> Effect Size	<i>P</i> Value [†]
	No. of Examinations	Mean*	Percentage of SAR Maximum (%)	No. of Examinations	Mean*	Percentage of SAR Maximum (%)		
SAR (W/kg)								
Total	81 535	1.09 ± 0.69	54	12 229	1.14 ± 0.61	57	0.07	<.001
CNS	59 947	1.05 ± 0.71	52	7 511	1.06 ± 0.63	53	0.07	<.001
Body	21 588	1.21 ± 0.60	60	4 718	1.25 ± 0.54	62	0.18	<.001
SED (J/kg)								
Total	81 535	33 ± 27	...	12 229	38 ± 26	...	0.18	<.001
CNS	59 947	33 ± 28	...	7 511	37 ± 26	...	0.14	<.001
Body	21 588	32 ± 22	...	4 718	39 ± 24	...	0.30	<.001

Note.— Percentage of specific absorption rate (SAR) maximum shows the proportion of SAR reached with respect to the 2 W/kg cutoff set by the International Electrotechnical Commission for normal operating mode. Cohen *d* effect sizes are as follows: minimal, less than 0.20; small, 0.20–0.49; medium, 0.50–0.79; and large, 0.80 or more. CNS = central nervous system, SED = specific energy dose.

* Data are mean ± standard deviation.

[†] Two one-sided tests for equivalence showed that all the mean values at 1.5 and 3.0 T were statistically equivalent assuming a Cohen *d* effect size of 0.5 (two one-sided tests, *P* < .05).

.001) (Table 1). The mean number of sequences performed at our institution was equivalent at 3.0 and 1.5 T for fetal body MRI (31 sequences ± 11 vs 28 ± 10) and fetal CNS MRI (25 sequences ± 7 vs 24 sequences ± 6) (TOST, *P* < .001) (Fig 2). The most frequently used sequences for both scanner strengths were SSTSE, EPI, and SSFP (Table E2 [online]). The sequences with the longest acquisition time for both scanners were SSTSE and SSFP (Table E3 [online]).

SAR and SED by Field Strength

The 3.0-T sequences collectively showed a higher SAR than did the 1.5-T sequences. However, the mean SAR at 1.5 T (1.09 W/kg ± 0.69) was statistically equivalent to the mean SAR at 3.0 T (1.14 W/kg ± 0.61) (TOST, *P* < .001). The percentages of maximum SAR at 1.5 T (54%) and 3.0 T (57%) were calculated based on the 2 W/kg upper limit set by the IEC for a normal operating mode and showed a small 3% increase in SAR when moving from 1.5 to 3.0 T (Table 2, Fig 3). SAR ranged from 0.01 to 2.91 W/kg at 1.5 T and from 0.02 to 2.24 at 3.0 T. Similarly, the mean SED per sequence (33 J/kg ± 27 vs 38 J/kg ± 26) and the accumulated SED per MRI (965 J/kg ± 408 vs 996 J/kg ± 366, +0.2%) were statistically equivalent between 1.5 T and 3.0 T (TOST *P* < .001). The percentages of maximum accumulated SED at 1.5 T (6.9%) and 3.0 T (7.1%) were calculated based on the 14 000 J/kg cutoff established by the IEC and showed a 0.2% increase in accumulated SED from 1.5 T to 3.0 T (Table 3, Fig 4).

SAR and SED by Clinical Indication

For fetal CNS MRI, mean SAR (1.05 W/kg ± 0.71 vs 1.06 W/kg ± 0.63) and SED (33 J/kg ± 28 vs 37 J/kg ± 26) at 1.5 and 3.0 T were statistically equivalent (TOST, *P* < .001). The percentages of maximum SAR at 1.5 T (52%) and 3.0 T (53%) were calculated based on the 2 W/kg upper limit set by the IEC for a normal operating mode and showed a small 1% increase in SAR from 1.5 to 3.0 T. When evaluating the

accumulated SED of all sequences per MRI examination, the mean values at 1.5 T (1038 J/kg ± 430) and 3.0 T (1045 J/kg ± 385) were statistically equivalent (+0.1%; TOST, *P* < .001).

For fetal body MRI, mean SAR at 1.5 and 3.0 T (1.21 W/kg ± 0.60 and 1.25 W/kg ± 0.54, respectively; +2%; TOST, *P* < .001) and mean SED at 1.5 T and 3.0 T (32 J/kg ± 22 and 39 J/kg ± 24, respectively; TOST, *P* < .001) were statistically equivalent (Table 2). The percentages of maximum SAR at 1.5 T (60%) and 3.0 T (62%) were calculated based on the 2 W/kg upper limit set by the IEC for a normal operating mode and showed a small 2% increase in SAR from 1.5 to 3.0 T. However, the accumulated SED obtained for fetal body MRI at 3.0 T (mean, 929 J/kg ± 327) and 1.5 T (801 J/kg ± 292) were not statistically equivalent (+0.9%; TOST, *P* = .14) (Table 3).

SAR and SED by Specific Sequences

Sequences with the highest mean SAR at both 1.5 and 3.0 T were SSTSE (1.59 and 1.55 W/kg, respectively), 2D SSFP (1.56 and 1.55 W/kg, respectively), and cine SSFP (1.52 and 1.56, respectively) (Table 4). The EPI sequence yielded the lowest SAR for both 1.5- (0.11 W/kg) and 3.0-T (0.24 W/kg) MRI.

The mean SAR for specific sequences was statistically equivalent at 1.5 and 3.0 T for SSTSE (1.59 W/kg ± 0.09 and 1.55 W/kg ± 0.16, respectively), 2D SSFP (1.56 W/kg ± 0.11 and 1.55 W/kg ± 0.14, respectively), and cine SSFP (1.52 W/kg ± 0.15 and 1.56 W/kg ± 0.11, respectively) (TOST, *P* < .001). The following sequences did not show statistical equivalence and displayed the largest effect size: 2D T1-weighted SPGR (Cohen *d* effect size = 3.33), 3D T1-weighted SPGR (Cohen *d* effect size = 1.88), EPI (Cohen *d* effect size = 0.83), and 3D SSFP (Cohen *d* effect size = 0.80). The percentages of maximum SAR at 1.5 and 3.0 T calculated based on the 2 W/kg upper limit set by the IEC for a normal operating mode per sequence are shown in Table 4. Figure 5 shows the distribution of the mean difference in SAR by different sequences and their respective equivalence bounds.

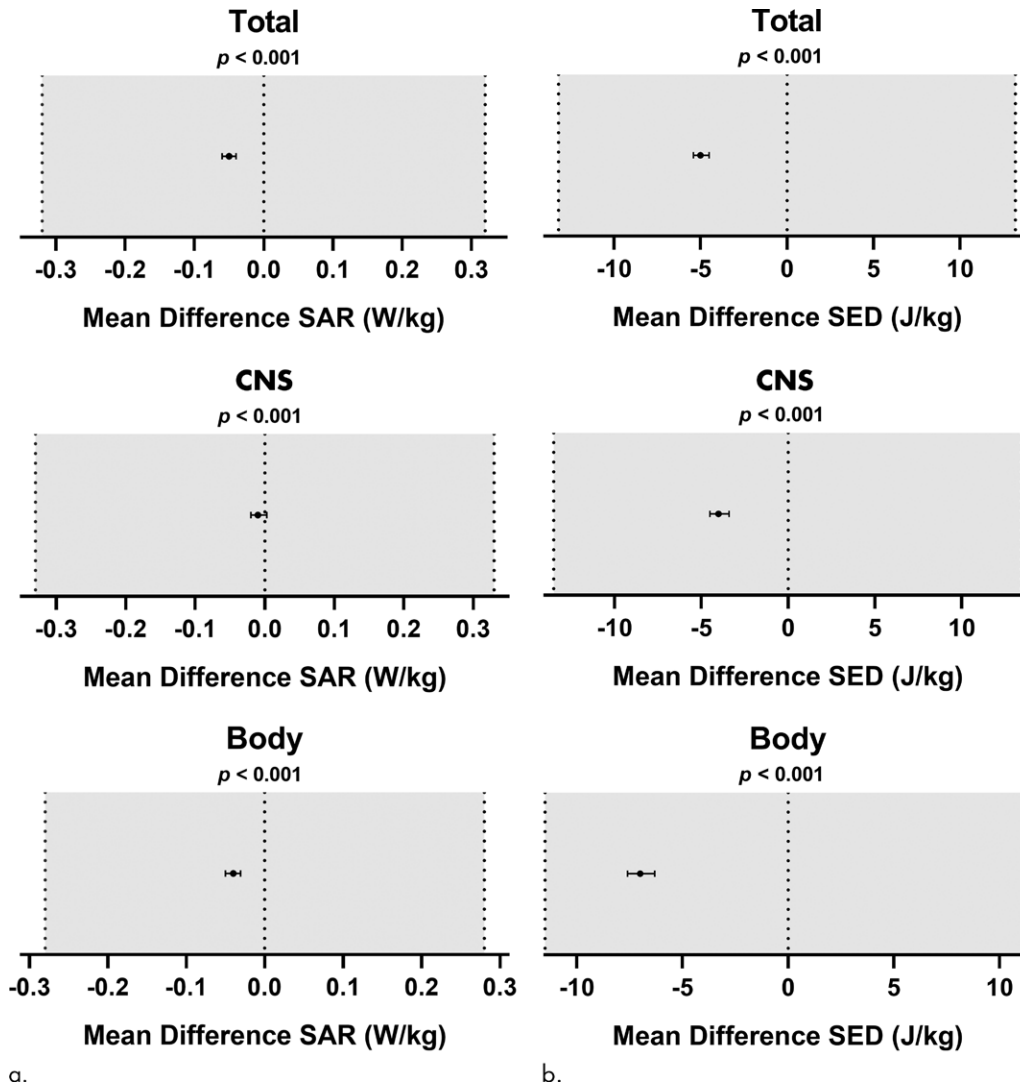


Figure 3: Plots of the two one-sided test results show significant statistical equivalence between 1.5- and 3.0-T MRI according to (a) specific absorption rate (SAR) and (b) specific energy dose (SED). The mean difference (•) and the 95% confidence interval (horizontal line) are graphed in comparison to equivalence bounds in raw scores (dashed lines) and are calculated based on an effect size of 0.50. Statistical significance was defined as $P < .05$. The mean difference was calculated by subtracting the SAR and SED at 1.5 T from the values obtained at 3.0 T. CNS = central nervous systems.

Table 3: Accumulated SED per Examination according to Field Strength and MRI Protocol

Examination	1.5 T			3.0 T			Cohen <i>d</i> Effect Size	<i>P</i> Value
	No. of Examinations	Mean SED (J/kg)*	Percentage of SED Maximum (%)	No. of Examinations	Mean SED (J/kg)*	Percentage of SED Maximum (%)		
Total	2784	965 ± 408	6.9	463	996 ± 366	7.1	0.07	<.001†
CNS	1926	1038 ± 430	7.4	267	1045 ± 385	7.5	0.01	<.001†
Body	858	801 ± 292	5.7	196	929 ± 327	6.6	0.41	.14

Note.—Percentage of specific energy dose (SED) maximum shows the proportion of accumulated SED reached with respect to the 14 000 J/kg cutoff set by the International Electrotechnical Commission. Cohen *d* effect sizes are as follows: minimal, less than 0.20; small, 0.20–0.49; medium, 0.50–0.79; and large, 0.80 or more. CNS = central nervous system.

* Data are mean ± standard deviation.

† Values that are statistically equivalent ($P < .05$) based on the two one-sided equivalence test assuming a Cohen *d* effect size of 0.5.

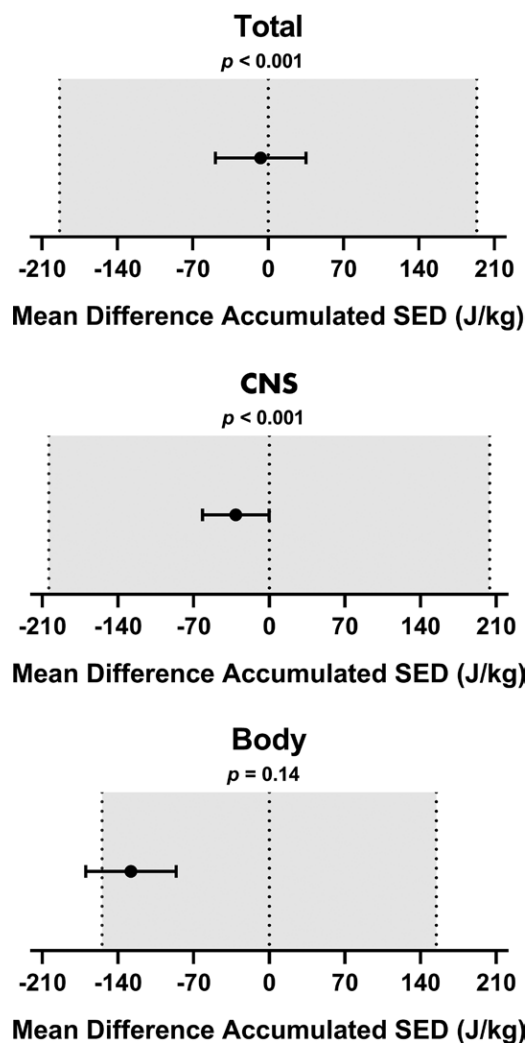


Figure 4: Plots of the two one-sided test results show statistical equivalence between 1.5- and 3.0-T MRI in terms of accumulated specific energy dose (SED) in the total sample and central nervous system (CNS) protocol. However, the accumulated SED was found to be not statistically equivalent for the body protocol, as the lower 95% confidence interval (CI) fell outside the equivalence bounds (dashed lines). The mean difference (•) and 95% CI (horizontal line) are graphed in comparison to equivalence bounds in raw scores calculated based on an effect size of 0.50. Statistical equivalence was defined as $P < .05$. The mean difference was calculated by subtracting the SAR and SED at 1.5 T from the values obtained at 3.0 T.

The mean SED per specific sequence was statistically equivalent at 1.5 and 3.0 T for cine SSFP (56 J/kg \pm 11 and 58 J/kg \pm 10, respectively) and SSTSE (51 J/kg \pm 19 and 56 J/kg \pm 18, respectively) (TOST, $P < .001$). The remaining sequences did not show statistical equivalence (Table 4). The largest SED effect sizes were observed for the following sequences: 2D T1-weighted SPGR (Cohen d effect size = 2.12), 3D SSFP (Cohen d effect size = 1.66), 2D SSFP (Cohen d effect size = 0.87), and EPI (Cohen d effect size = 0.68). Figure 6 shows the distribution of the mean difference in SED by different sequences and their respective equivalence bounds.

In total, 99.9% (93 643 of 93 764) of sequences had an SAR of 2 W/kg or less (ie, the upper limit for MRI under a normal operating mode). The other 0.1% (121 of 93 764) of sequences had an SAR greater than 2 W/kg. The number of sequences

with an SAR greater than 2 W/kg was not different between the 1.5- ($n = 112$) and 3.0-T ($n = 9$) scanners (χ^2 test, $P = .06$). The sequences in this group were distributed as follows: SSTSE (67.8%, 82 of 121), cine SSFP (15.7%, 19 of 121), 2D SSFP (14.0%, 17 of 121), 3D SSFP (1.7%, two of 121), and T1-weighted SPGR (0.8%, one of 121).

Discussion

Heating is a concern when using high-field-strength MRI for fetal imaging. When compared with 1.5-T MRI, 3.0-T MRI is associated with increased energy deposition that may lead to undesired fetal heating. Our findings suggest that in most cases, the specific absorption rate (SAR) and specific energy dose (SED) imposed on the gravid patient at 1.5 and 3.0 T at first-level scanning are statistically equivalent for SAR (1.09 and 1.14 W/kg, respectively; Schuirman two one-sided test [TOST], $P < .001$) and SED (33 and 38 J/kg, respectively; TOST, $P < .001$) and are well below the level permitted by the International Electrotechnical Commission (99% of all sequences). The total amounts of energy delivered at 1.5 and 3.0 T were also statistically equivalent (965 and 996 J/kg, respectively; TOST, $P < .001$). The single-shot turbo spin-echo (SSTSE) sequence, which had the highest SAR and SED and was the most used MRI sequence, showed statistically equivalent SAR (1.59 and 1.55 W/kg; TOST, $P < .001$) and SED (51 and 56 J/kg; TOST, $P < .001$) at 1.5 and 3.0 T, respectively. However, findings suggested that some 3.0-T sequences, such as the two-dimensional (2D) T1-weighted spoiled gradient-echo (SPGR) and three-dimensional (3D) steady-state free precession (SSFP) sequences, may require modifications.

One of the primary safety concerns of scanning the fetus with a higher field strength is the higher power created and transferred, which translates to higher temperatures for the fetus. In humans, neural tube and facial defects have been found in children whose mothers had experienced prolonged periods of hyperthermia during the first trimester of pregnancy (20,21). For this reason, it is imperative that the temperature of the gravid patient and her fetus be well controlled during MRI.

Fetal 3.0-T MRI protocols can be tailored to deliver equivalent SAR and SED compared with those delivered by a 1.5-T scanner. Krishnamurthy et al evaluated a modified SSTSE sequence for their fetal MRI protocol and reported a lower SAR at 3.0 T than at 1.5 T by decreasing the flip angle and increasing the repetition time (22). Although these modifications may bring undesirable trade-offs, such as a longer scanning time and reduced image quality, this sequence still showed a higher signal-to-noise ratio and increased image quality at 3.0 T compared with sequences at 1.5 T (22).

SAR varies depending on the type of sequence, as it is heavily associated with the radiofrequency pulse and repetition time. Some sequences in our cohort, such as 2D T1-weighted SPGR, 3D SSFP, and EPI, showed higher SAR and SED at 3.0 T and were not statistically equivalent when compared with SAR and SED at 1.5 T. However, these sequences are among the least used per MRI examination, and some even displayed the lowest SAR and SED values in our sample. Finally, only 0.01% of the sequences surpassed the SAR limit, with no significant difference

Table 4: SAR and SED for Each Sequence and Equivalence Tests according to Field Strength

Parameter	1.5 T			3.0 T			Cohen <i>d</i> Effect Size	<i>P</i> Value
	No. of Examinations	Mean*	Percentage of SAR Maximum (%)	No. of Examinations	Mean*	Percentage of SAR Maximum (%)		
SAR (W/kg)								
SSTSE	43749	1.59 ± 0.09	80	5856	1.55 ± 0.16	77	0.30	<.001 [†]
Cine SSFP	2876	1.52 ± 0.15	76	280	1.56 ± 0.11	78	0.30	<.001 [†]
2D SSFP	4319	1.56 ± 0.11	78	1059	1.55 ± 0.14	77	0.07	<.001 [†]
3D SSFP	1292	1.44 ± 0.11	72	324	1.55 ± 0.16	77	0.80	>.99
2D T1w SPGR	3632	0.43 ± 0.07	21	972	1.18 ± 0.31	59	3.33	.20
3D T1w SPGR	1576	1.47 ± 0.20	73	255	1.09 ± 0.22	54	1.88	>.99
EPI	24091	0.11 ± 0.11	5	3483	0.24 ± 0.19	12	0.83	>.99
SED (J/kg)								
SSTSE	43749	51 ± 19	...	5856	56 ± 18	...	0.27	<.001 [†]
Cine SSFP	2876	56 ± 11	...	280	58 ± 10	...	0.19	<.001 [†]
2D SSFP	4319	35 ± 11	...	1059	46 ± 14	...	0.87	>.99
3D SSFP	1292	17 ± 6	...	324	27 ± 6	...	1.66	>.99
2D T1w SPGR	3632	10 ± 8	...	972	26 ± 7	...	2.12	>.99
3D T1w SPGR	1576	27 ± 8	...	255	22 ± 6	...	0.70	>.99
EPI	24091	2 ± 3	...	3483	8 ± 12	...	0.68	>.99

Note.—Cohen *d* effect sizes are as follows: minimal, less than 0.20; small, 0.20–0.49; medium, 0.50–0.79; and large, 0.80 or more. EPI = echo planar imaging, SAR = specific absorption rate, SED = specific energy dose, SPGR = spoiled gradient echo, SSFP = steady-state free precession, SSTSE = single-shot turbo spin echo, T1w = T1 weighted, 3D = three-dimensional, 2D = two-dimensional.

* Data are mean ± standard deviation.

[†] Two one-sided equivalence test (TOST) showed all the mean values at 1.5 and 3.0 T were statistically equivalent assuming a Cohen *d* effect size of 0.5 (TOST, *P* < .05). Percentage of SAR maximum shows the proportion of SAR reached with respect to the 2 W/kg cutoff set by the International Electrotechnical Commission for normal operating mode.

in terms of field strength, and the raw mean difference in terms of SAR and SED for most sequences was not important enough to raise concerns at our institution regarding SAR and SED at 3.0 T.

SAR is a main determinant of MRI safety and represents a surrogate measurement of the power deposited by the radio-frequency field onto the individual being examined. However, it is also an imperfect measurement of energy deposition that has been debated in the radiology literature. Previous studies showed commercial scanners tend to overestimate SAR by up to 2.2-fold when compared with direct thermal estimation (10,23).

Similarly, studies performed using a model of a pregnant patient showed that local SAR in the fetus is heterogeneous and may exceed recommended limits once the maternal whole-body average SAR reaches 2 W/kg (24,25). This heterogeneity may yield focal spots of high SAR (ie, hotspots) in specific body tissues that are sensitive to local temperature increases. However, Hand et al published a study with anatomically realistic models of 28-weeks-pregnant patients and showed that the highest local SAR is in the mother, with the fetus being exposed to a peak of approximately 40%–60% of that value at 64 MHz and 50%–70% of it at 127 MHz (25). For these reasons, the SAR reported by the scanner should be interpreted carefully, while noting there will be some degree of inaccuracy.

The accumulated SED transferred per MRI examination to the patient was statistically equivalent between 3.0 and 1.5 T. Although most sequences did not show an equivalent mean SED

at 3.0 T compared with that at 1.5 T, this did not translate into a higher accumulated SED per MRI. The higher signal-to-noise ratio obtained with a higher field strength may result in fewer sequences needed to make a reliable interpretation at 3.0 T compared with those needed at 1.5 T (2,13,22). With algorithms that correct for fetal motion and improve image quality, the number of acquisitions required could be reduced even further going forward (26).

Our study had limitations. First, although there are regulatory limits, there is no standardized method to estimate SAR, and these values may differ across manufacturers. SAR values from one scanner should be considered as a quantitative estimate compared with values from other scanners. Second, it is not accurate to compare the safety profile of 1.5- and 3.0-T scanners solely based on SAR and SED; however, there is no current method to calculate fetal temperature separate from maternal temperature in vivo in humans. However, our goal was to show that fetal 3.0-T MRI yielded equivalent safety energy metrics compared with 1.5-T MRI. Finally, the acquisition time obtained from the Digital Imaging and Communications in Medicine headers may not be perfectly accurate. These values are used by the scanner's manufacturer for internal quality assessment and are not recorded for research purposes.

In conclusion, fetal MRI examinations performed at 1.5 and 3.0 T share equivalent energy metrics. Sequences, such as T1-weighted two-dimensional spoiled gradient-echo and

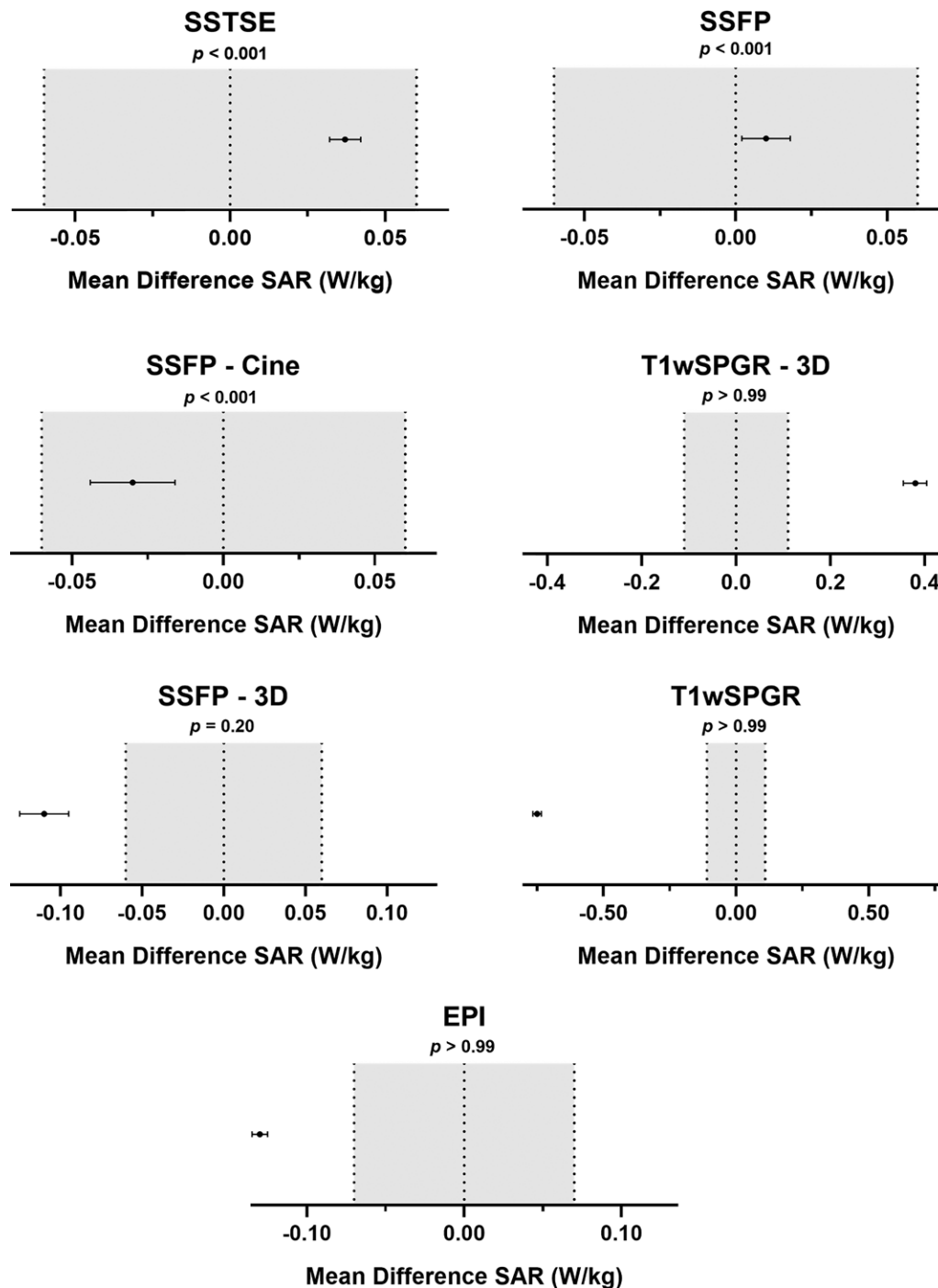


Figure 5: Plots of the two one-sided test results show statistical equivalence between 1.5- and 3.0-T MRI in terms of specific absorption rate (SAR) according to sequence. Three-dimensional T1-weighted spoiled gradient-echo (T1wSPGR-3D), three-dimensional steady-state free precession (SSFP-3D), two-dimensional T1-weighted spoiled gradient-echo (T1wSPGR), and echo-planar imaging (EPI) sequences did not show statistical equivalence, as their 95% confidence intervals (CIs) fell outside the equivalence bounds (vertical dashed lines). The mean difference (•) and the 95% CI (horizontal line) are graphed in comparison to equivalence bounds in raw scores calculated based on an effect size of 0.50. Statistical equivalence was defined as $P < .05$. The mean difference was calculated by subtracting SAR at 1.5 T from SAR at 3.0 T. SSFP = two-dimensional steady-state free precession, SSTSE = single shot turbo spin echo.

three-dimensional steady-state free precession, require modification to keep the energy delivered to the patient as low as possible.

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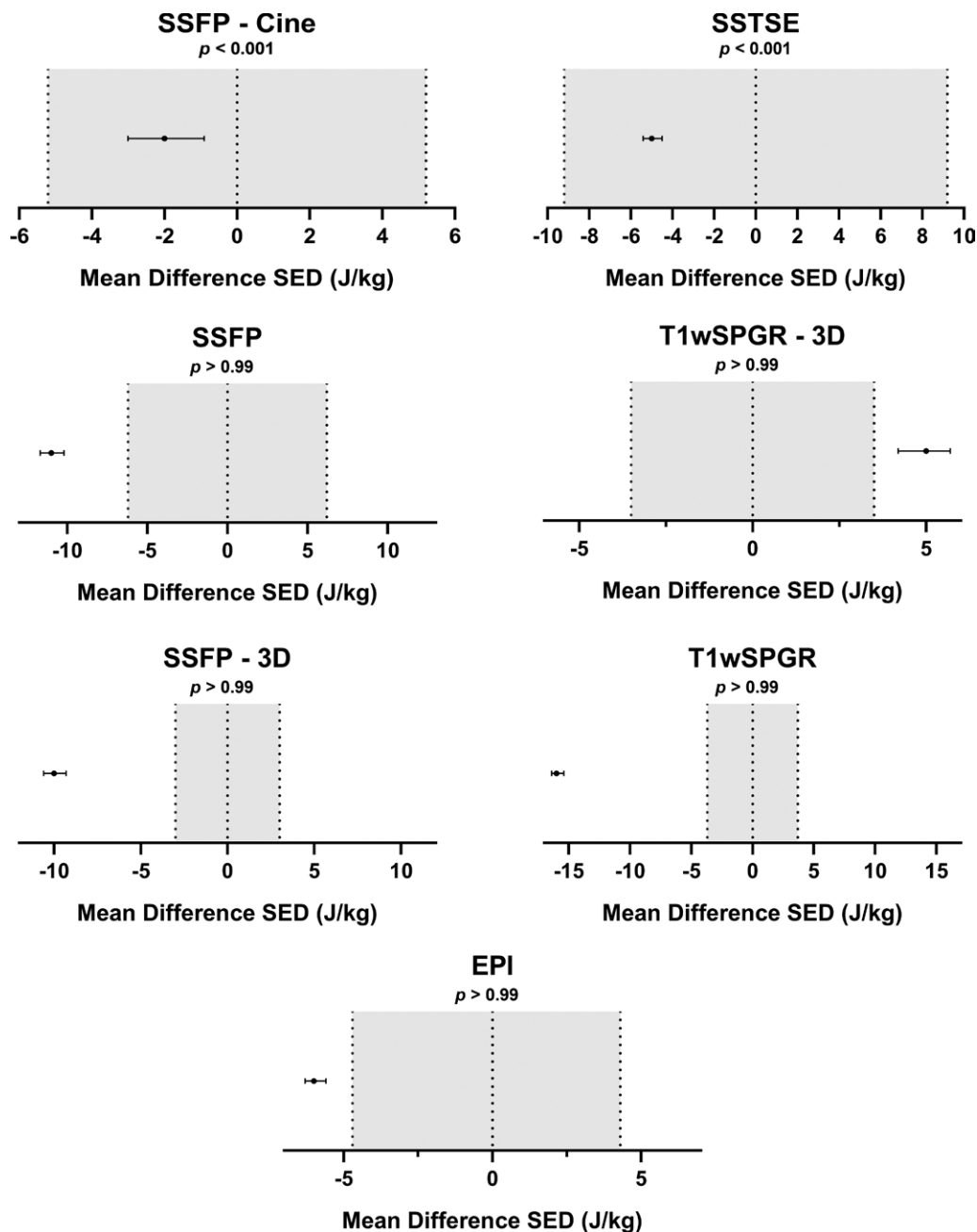


Figure 6: Plots of the two one-sided test results show statistical equivalence between 1.5 and 3.0 T in terms of specific energy dose (SED) according to sequence. Two-dimensional steady-state free precession (SSFP), three-dimensional T1-weighted spoiled gradient-echo (T1wSPGR-3D), three-dimensional steady-state free precession (SSFP-3D), two-dimensional T1-weighted spoiled gradient-echo (T1wSPGR), and echo-planar imaging (EPI) did not show statistical equivalence, as their 95% confidence intervals (CIs) fell outside the equivalence bounds (vertical dashed lines). The mean difference (•) and the 95% CI (horizontal line) are graphed in comparison to equivalence bounds in raw scores calculated based on an effect size of 0.50. Statistical equivalence was defined as $P < .05$. The mean difference was calculated by subtracting SED at 1.5 T from SED at 3.0 T. SSTSE = single-shot turbo spin echo.

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