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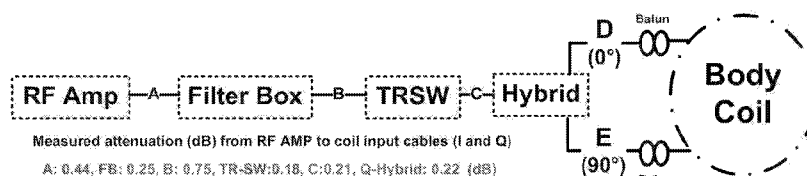
(54) **Title:** HIGH DYNAMIC RANGE RF POWER MONITOR

FIG. 1

(57) **Abstract:** A device with at least one channel for measuring high dynamic range, radio frequency (RF) power levels over broad-ranging duty cycles includes a power sensor circuit comprising at least one logarithmic amplifier; at least one directional RF coupler electrically connected to the at least one power sensor; at least one RF attenuator electrically connected to the at least one RF coupler; and at least one sampling circuit electrically connected to the at least one RF attenuator and the at least one RF coupler. The at least one sampling circuit performs analog-to-digital conversion of electrical signals received to provide digitals signals for measuring the RF power level in the at least one channel.

HIGH DYNAMIC RANGE RF POWER MONITOR

CROSS-REFERENCE OF RELATED APPLICATION

[0001] This application claims priority to U.S. Provisional Application No. 61/466,194 filed March 22, 2011, the entire contents of which are hereby incorporated by reference.

[0002] This invention was made with U.S. Government support of Grant Nos. R01 EB07829, awarded by National Institutes of Health (NIH). The U.S. Government has certain rights in this invention.

BACKGROUND

1. Field of Invention

[0003] The field of the currently claimed embodiments of this invention relates to high dynamic range (DR) radio frequency (RF) power monitoring devices and methods.

2. Discussion of Related Art

[0004] Accurate knowledge of the RF specific absorption rate (SAR) in the body during magnetic resonance imaging (MRI) scans is important for patient safety and compliance with limits mandated by the Food and Drug Administration (FDA) in the USA¹ and the International Electro-technical Commission (IEC) in Europe.² In addition to ensuring safe operation and regulatory compliance, accurate power monitoring can avoid restrictions on clinical MRI sequences arising from incorrect estimation of the delivered power. Accurate knowledge of delivered power is essential for testing the MRI safety of peripheral, implanted and interventional devices at defined RF exposure levels.³⁻⁶

[0005] RF safety concerns initially arose with the introduction of higher-field 1.5 Tesla (T) whole-body MRI scanners and the recognition that SAR increases approximately with the square of MRI frequency or field-strength when other MRI sequence

parameters are kept constant.⁷⁻⁹ The recent emergence of clinical 3 T scanners and experimental body systems operating at 7 T and higher,¹⁰ in which SAR could potentially increase 4- to more than 20-fold compared to 1.5T, only exacerbates concerns about safety and how to ensure compliance with SAR guidelines.^{1, 2}

[0006] In clinical MRI scanners, SAR monitoring for safety and regulatory compliance is generally carried out by scanner software and hardware that is largely proprietary, with “scanner SAR” values typically logged for each study. These systems prohibit or terminate scanning based on predictions of body SAR relying on internal measures, modeling, and prior characterization or assumed properties of the MRI transmit coil. Electromagnetic modeling with knowledge of the input power¹¹⁻¹³ and thermal mapping^{14, 15} can help provide a detailed understanding of whole body and local SAR. Yet, rare as they may be compared to the total number of MRI scans performed, RF burns do occur, a fraction of which are reported to the FDA.¹⁶ In these cases, at least, a failure in scanner SAR monitoring has occurred.

[0007] Unfortunately, investigating whether the scanner is operating safely within SAR guidelines by means that are independent of the scanner, if performed at all, is not easy.¹⁷ The accuracy of scanner SAR estimates is also questionable in light of discrepancies with thermally-derived SAR measurements,^{17, 18} especially during MRI safety-testing of interventional devices^{3, 18-20} and the lack of correlation between subjective heat perception by patients and scanner SAR.²¹

[0008] Setting precise SAR exposure levels for investigators testing devices or MRI methods, or for evaluating SAR in individual burn cases,²² requires accurate and independent measurement tools. This starts with accurate measurements of the total power deposited and requires a reliable RF power meter. The RF power monitors built into the MRI scanner are usually attached to the RF power amplifier output. However, measuring the power delivered to the body is complicated by losses in the RF transmission chain, including the cables, switches, the quadrature-hybrid (Q-hybrid) and the MRI coil.^{23, 24} These losses can vary over time, but are not routinely monitored.

[0009] Moreover, as we now report, the very high dynamic range (typically >20 dB) (DR=peak-to-average power ratio) of RF transmit pulses, and MRI duty cycles that span orders-of-magnitude, are beyond the capabilities of available commercial power meters.²⁵ These meters are adequate for pulse sequences with short repetition periods (TR) and consistent high power levels. However, they do not give accurate results for sequences using mixtures of high and low amplitudes or modulations, or long TR. There thus remains a need for improved systems and methods for measuring high dynamic range, low duty cycle (typically < 1%) RF power.

SUMMARY

[0010] A device with at least one channel for measuring high dynamic range, radio frequency (RF) power levels over broad-ranging duty cycles according to an embodiment of the current invention includes a power sensor circuit comprising at least one logarithmic amplifier; at least one directional RF coupler electrically connected to the at least one power sensor; at least one RF attenuator electrically connected to the at least one RF coupler; and at least one sampling circuit electrically connected to the at least one RF attenuator and the at least one RF coupler. The at least one sampling circuit performs analog-to-digital conversion of electrical signals received to provide digital signals for measuring the RF power level in the at least one channel.

[0011] A method of monitoring RF exposure proximate an RF emitting device according to an embodiment of the current invention includes connecting an RF monitoring system according to an embodiment of the current invention to an RF power source of said RF emitting device.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Further objectives and advantages will become apparent from a consideration of the description, drawings, and examples.

[0013] **FIG. 1** is a schematic illustration of the Philips Achieva RF power delivery chain provided to facilitate a description of some embodiments of the current invention. Shown are the RF amplifier (RF AMP), measured cable attenuation factors (A, B, C), the filter box penetrating the scanner's Faraday cage, the transmit switch (TRSW) and the Q-hybrid.

[0014] **FIG. 2A** provides a circuit diagram of a digital power sensor circuit (PSC) based on the AD8310 IC according to an embodiment of the current invention. **FIG. 2B** shows an example of one of the three power profiling measurement modules (PPMM) showing the directional coupler and PSCs according to an embodiment of the current invention.

[0015] **FIG. 3** is a schematic illustration of a device for measuring high dynamic range, low duty cycle radio frequency (RF) power levels according to an embodiment of the current invention.

[0016] **FIG. 4A** is a schematic illustration of a bench setup for calibrating the Power Sensor Circuit (PSC) units as well as testing dynamic range and linear performance according to an embodiment of the current invention. **FIG. 4B** shows a calibration curve, PSC vs. Ladybug meter showing linearity. **FIG. 4C** shows PSC 90 dB dynamic range.

[0017] **FIG. 5** is a schematic illustration of a resonant circuit for an MRI coil producing a certain transverse RF magnetic field, BI , to facilitate an explanation of some concepts of the current invention. R_c is the coil resistance and R_s is the resistance reflected into the coil circuit by the imaging subject load. BI is proportional to current I in the coil and $\text{Power loss} = I^2 \cdot (R_c + R_s)$, where R_c is the coil resistance and R_s is the sample resistance at the RF, and I is the coil current. Shown also are pickup loops used by the scanner to monitor the BI RF field produced by the coil.

[0018] **FIGS. 6A-6C** show real-time profile of a ~ 7 ms asymmetric, slice selective RF pulse in the Philips scanner. **FIG. 6A** shows scanner BI linear pulse envelope simulator. **FIG. 6B** shows recorded time window of RF power in real time for long RF pulses. **FIG. 6C** shows a single pulse (logarithmic scale).

[0019] **FIGS. 7A-7C** show results for some measurements according to an embodiment of the current invention. **FIG. 7A** shows Philips Medical System's 3 Tesla (T) Achieva amplifier output power measurements using the PPMM (solid circles), and the scanner power monitoring unit (open diamonds, reported in the log file), vs. scanner average predicted power. Power data are from 11 human volunteers, plus four measurements from mineral oil bottles (circled), using short (1 ms) and long (7 ms) slice-selective pulses. The line represents identity. **FIG. 7B** shows total power deposited in the body measured by the PPMM, as a function of BMI. Lines of best fit correspond to long and short pulses. Also shown is the PPMM-measured whole-body SAR for (**FIG. 7C**) short and (**FIG. 7D**) long pulses, as compared to the scanner predicted SAR from scanner log files (horizontal lines).

[0020] **FIGS. 8A-8B** show measured SAR for 6 volunteers on the Siemens Medical System's 3 T system (solid dots) compared to scanner reported values from (8A) the log file and (8B) the scanner console.

DETAILED DESCRIPTION

[0021] Some embodiments of the current invention are discussed in detail below. In describing embodiments, specific terminology is employed for the sake of clarity. However, the invention is not intended to be limited to the specific terminology so selected. A person skilled in the relevant art will recognize that other equivalent components can be employed and other methods developed without departing from the broad concepts of the current invention. All references cited anywhere in this specification, including the Background and Detailed Description sections, are incorporated by reference as if each had been individually incorporated.

[0022] Some embodiments of the current invention provide a high-DR, MRI-compatible, power profiling system for measuring and recording RF power over a wide range of MRI scan conditions. The system is broadband up to 440 MHz, can be used to sample power for both local and whole-body power flow and, unlike commercial meters, has six channels and a buffer size suitable for monitoring power at multiple locations over extended time periods. We provide some examples of its

application to real-time RF power monitoring in human whole-body MRI studies of volunteers performed in commercial Philips Medical Systems' (Best, The Netherlands) and Siemens Medical Solutions' (Malvern, PA) 3 T MRI scanners. We show that the power deposited and the body-average SAR,^{1, 2} often vary considerably from the scanners' own estimates.

RF power measurement

[0023] In an example, the losses in the RF power chain of a Philips 3 T *Achieva* 3 T scanner²⁶ were first characterized using a 4395A Agilent Technologies (Santa Clara, CA) network analyzer by measuring the attenuation in each stage in accordance with the schematic in Figure 1. Measured losses in these components show that the power output at the Q-hybrid (points D, E, Figure 1) is only about 59% of the power out of the RF amplifier (point A). (See, for example, U.S. Pat. Pub. No. 2011/0148411; U.S. App. No. 12/677,097 assigned to the same assignee as the current application, the entire content of which is incorporated herein by reference.)

[0024] To measure the pulse power during MRI, we first tried commercial inline power meters. Bird 5014 and Bird 5010b (*Bird Technologies, Solon, OH*) did not work correctly for peak/average power ratios greater than ten. Even when operating the scanner at minimum TRs and low RF field intensity (B_1), measurements were unstable and irreproducible.

[0025] We next used a Ladybug Technologies LLC (Santa Rosa, CA), LB480A power profiling meter in combination with 50 dB dual directional couplers to measure forward and reverse power at the outputs of the power amplifier and the Q-hybrid during MRI. The Ladybug meter sampled the pulse profile at 10 μ s intervals and stored results for power calculations. While this yielded accurate measurements on four volunteers,²⁷ the use of USB cables from Ladybug to the computer necessitated a person inside the scanner room. Moreover, the Ladybug meter did not have sufficient channels for monitoring the forward and reverse power at the three locations of interest simultaneously (A, D, and E in Figure 1, location A). In addition, its small buffer size (≤ 1 sec) was inadequate for providing continuous

measurements of power for many MRI sequences with long TRs over the several cycles needed for accurately measuring time-averaged power, thus rendering real-time measurements impractical.

[0026] We therefore built a 6-channel scanner-independent power monitoring system according to an embodiment of the current invention. An embodiment has six power sensor circuits (PSC), (Figure 2A) assembled from AD8310 logarithmic amplifier IC's (Analog Devices, Norwood MA). At each of three locations (RF amplifier output, two Q-hybrid outputs), a power profiling measurement module (PPMM) having a 50 dB directional coupler (Werlatone Inc., Patterson NY) connected to two PSCs, one to its forward channel and one to its reverse channel (Figure 2B), was deployed. A 10 dB attenuator was added to the forward channels to allow measurements of up to 50 kW of peak power. The design DR was from 17 dBm (nearly the maximum input power of the AD8310) to -80 dBm over the desired frequency range 1-440MHz. Each PSC is powered by a rechargeable lithium ion, non-magnetic 4V battery (PowerStream, Orem UT) and can operate continuously for at least 10 hours before recharging. The video bandwidth of the ICs was set to 112 KHz using a 470 PF capacitor (Figure 2A).

[0027] Although this embodiment describes three circuits, such as the one illustrated in the embodiment of Figures 2A and 2B, one, two, three or more such circuits could be used in various embodiments of the current invention.

[0028] The outputs of each of the six PSCs are simultaneously sampled in differential input mode at 200 kHz by a 16 bit USB-6251 National Instruments (Austin, TX) data acquisition system controlled by a laptop computer that also stores the power measurement data. The 5 μ s sampling resolution accurately captures the MRI RF pulse modulation whose time resolution in the Philips scanner was about 6.4 μ s. A MATLAB (The Mathworks, Natick, MA) program was written to read the saved voltage files, convert them to power profiles using the linear calibration curves for each channel, and to calculate average power values for all experiments. A schematic of the system configured to monitor RF power flow is shown in Figure 3.

The (low frequency) power profiling lines from the PPMMs attached to the quad hybrid outputs are fed through the scanner room's connection panel. The lines from the PPMM connected to the RF power amplifier were wound around ferrite cores to prevent RF interference.

[0029] Each PPMM was bench calibrated for the operational frequencies of the Philips 3 T Achieva scanner and a Siemens 3 T Trio scanner (127.8 MHz and 123 MHz, respectively) using the setup shown in Figure 4A. The calibration was performed against the LB480A meter using a 10 dBm frequency synthesizer whose output was connected to a 0-100dB variable attenuator to vary the input power level. The PSC voltage-to-logarithmic power was measured over a 70 dB range (limited by the LB480A unit's operational dynamic range) and was highly linear as shown in Figure 4. Figure 4B. The slopes of the calibration curves were about 0.24 V/10 dBm. The net sampling resolution of the A/D was set to 0.004 dBm. After calibration the full DR was tested over a range of 90 dB as shown in Figure 4C and exhibited a maximum deviation of 0.8 dBm from linearity at -80 dBm. The total insertion loss of the monitoring system PPMMs at 128 MHz was 0.1 dB or about 2%.

RF Power Deposition

[0030] Figure 5 shows a schematic resonant circuit for an MRI coil producing a transmit RF field, B_1 , proportional to the current, I , in the coil. The power loss in the circuit is the sum of the coil and subject losses in resistive loads R_C and R_S , respectively. The pickup loops, are fixed by the manufacturer inside the RF body coil. They are used by the scanner to monitor and set the initial value of the RF field produced by the coil during set-up. The power loss in the coil P_{coil} , is measured as the net power flow at the output of the Q-hybrid with a lossless sample placed in the coil. The lossless sample is a 1 liter bottle of mineral oil whose RF dielectric constant, conductivity and size are orders-of-magnitude lower than those of the body.^{28, 29} This was verified by measuring P_{coil} with additional mineral oil sample volumes of 2 liters and 3 liters; no significant change in power absorption was observed. The desired B_1 , and therefore the current I required to produce it, is

approximately constant, independent of the subject being imaged.^{30, 31} Therefore the coil power dissipation, P_{coil} , is constant for a given pulse sequence, independent of the subject. The power deposited in the subject is then $P_{subject} = P_{total} - P_{coil}$, where P_{total} is the total power dissipated in the coil plus the subject measured at the Q-hybrid. Note that larger subjects have greater P_{total} but the same P_{coil} .

[0031] To measure the RF power deposited in human subjects during MRI, the power monitoring system was connected to the output of the RF power amplifier and the two outputs of the Q-hybrid before the scan. Eleven healthy volunteers (9 men, 2 women; age 22–65 yrs) were recruited and provided informed consent for this study approved by The Johns Hopkins Institutional Review Board on Human Investigation. Subjects were positioned in the Philips 3T scanner and the scanner's automated scan preparation sequence initiated. Volunteers were landmarked at the xiphoid, placed at the isocenter of the scanner and a transverse slice containing both the heart and liver was targeted. A reference B1 RF field is first set based on pickup coil sensors, followed by the scanner's MRI-based B1 optimization algorithm which sets the final flip-angle. The B1 optimization algorithm is based on a stimulated echo sequence similar to the one described by Akoka *et al.*³² where an average signal projection is used, thus rendering the result stable against local field variations. Two field-echo (FE) MRI sequences with TR=50 ms and two different RF pulse shapes (a short 1 ms asymmetric two lobe pulse and a long 7 ms "Spredrex" pulse³³) were used.

[0032] The total scanner time per subject—including entry, positioning, and egress from the scanner—was 10-15 min.

[0033] The delivered RF power reported by the scanner, as well as the measured power output, was recorded. The subject was replaced by the mineral oil phantom and the pulse sequence repeated to produce the same B1 detected by the pickup coil. Scanner SAR and power were again recorded, along with the power measured by our power monitoring system. Body-average SAR was taken as the power deposited divided by the subject's weight, in accordance with the standard definition.^{1, 2}

[0034] The same protocol was repeated on six of the volunteers (men, age 23–66 yrs) in a Siemens 3T Trio scanner. The FE sequence used the scanner’s default 2ms RF sinc pulse with one side lobe. The scanner’s console SAR differed from the value reported in its log file, so both values were recorded.

[0035] All power values measured by our power monitoring system were calculated by averaging instantaneous power over a 0.5 s time window (10 pulses for FE pulse sequence).

RESULTS

[0036] MRI experiments showed no noticeable interference or image degradation with the PPMMs connected. Connecting the PPMMs did not increase noise, as was confirmed by noise scans acquired with the RF and gradients turned off.

[0037] Figure 6 exemplifies the 6-channel real-time recordings of an asymmetric, multi-lobe, slice selective RF pulse on the Philips scanner with a subject present. The detailed instantaneous recording of RF power is shown for Spredrex pulses on a logarithmic scale.³³

[0038] The results for the forward power delivered to the Philips body MRI coil and body average SAR for all subjects in the Philips scanner are plotted in Figure 7 as a function of the power reported by the scanner, the patient weight, and the body mass index (BMI). Figure 7A shows that the scanner-reported power at the RF amplifier’s output agrees with our PPMM system results to within 6% for short pulses (~1 ms). This is not true for longer pulses (~7 ms), where the scanner’s RF power monitoring fails when compared to the PPMM system that had been calibrated over the full DR and duty-cycles used for MRI. For all volunteers, the power delivered at the output of the Philips quadrature hybrid (Q-hybrid) is $56.5 \pm 2.5\%$ of the output of the amplifier. This figure is consistent with the 58.5% predicted from the measured losses in the Philips RF chain plus the measured insertion losses in the power monitoring modules. For the 50 ms TR, the average

power dissipated in the coil is 8.8 ± 0.6 W for the short pulses and 11.1 ± 0.8 W for the long pulses, independent of the size of the mineral oil bottle (1-3 liter).

[0039] The Philips Achieva scanner initially establishes a B1 that is the same for all samples using pickup loops. It is worth noting that the final MRI optimization yielded a B1 that was, on average, within 5% of the initial pickup loop B1 in all samples, from small to large human subjects as well as in the mineral oil bottles. This result supports the assumption that the current I required to produce a desired MRI flip angle across the slice projection is essentially independent of sample size, and that the power dissipation in the RF coil always equals the power dissipation with the mineral oil sample to a good approximation.

[0040] Figure 7B shows that the measured deposited power varies linearly with BMI with a correlation coefficient $R^2 = 0.8$ (0.7) for short (long) RF pulses. Figure 7C and Figure 7D show that the scanner almost always overestimates body-average SAR. The scanner overestimated SAR by up to 78% for short pulses and 123% for long pulses when compared to values obtained from our PPMM direct power determination and subject weights.

[0041] Figure 8 shows the calculated SAR values from the real-time power monitor versus the scanner reported values for 3T Siemens scanner. The power delivered at the output of the Q-hybrid is $90 \pm 2\%$ of the power measured at the RF amplifier output. SAR values listed in the Siemens log file differ from those reported at the console: Siemens does not state which values they use. In any case, as with the Philips scanner, the Siemens scanner overestimated SAR. The Siemens scanner log overestimated SAR by up to 103% while the console values were up to 71% above the actual measured SAR.

DISCUSSION

[0042] Some embodiments of the current invention address the problem of providing accurate real-time measurements of the RF power delivered to the body, which is inadequately served by existing technology. Specifically, we found that two

commonly available commercial RF power meters are unsuitable for the full range of DRs, duty cycles and pulse types encountered in MRI. This was further underscored by differences and errors in power monitoring for short and long RF pulses in the Philips scanner. We therefore developed a real-time, multi-channel power monitoring system according to an embodiment of the current invention that is suitable for a full range of MRI RF pulses and sequences operating over a frequency range that will accommodate scanners with fields up to 10 T.³⁴

[0043] The accuracy of measurements provided by our power monitoring system was independently validated three ways: 1) on the bench using the Ladybug power meter (Figure 4); 2) using the 3T scanner's power monitoring unit at the output of the amplifier for high-power, short RF pulses (Figure 7A); and 3) by measuring the losses in the 3T scanner's RF chain using our power monitor and comparing the results with independent measurements made with a network analyzer.

[0044] Our new power monitoring system was used to determine the true power deposited and the body-average SAR delivered to adult volunteers in two clinical 3 T MRI systems. The results showed that the scanners almost always overestimate the body-average SAR as compared to the actual power deposited. The overestimates were as much as 120% and 100%, respectively, in the Philips and Siemens 3T systems studied here (Figure 7C, 7D; Figure 8). Unfortunately, the exact details of the manufacturer's SAR modeling are proprietary, precluding the identification of specific causes for the differences. Nevertheless, the data in Figure 7 suggest Philips' use of a worst-case estimate that is independent of the subject loading, while Siemens' model evidently depends on the subject's weight (Figure 8). Although the evaluations were performed on the scanner's whole-body coils with sample-dominant losses, application of the power monitoring system is not limited by coil geometry, and similar measurements could be performed on other vendors' scanners and other coil sets, including multi-transmit systems at various field strengths.³⁴

[0045] The power monitoring system and protocol presented here provide measures of the total power deposited in the body during MRI, or the body average SAR defined as the total power divided by the subject's weight.^{1, 2} Local SAR exposure, such as peak 1-g or 10-g averages, are also important for safety compliance.^{1, 2} At present, these must be obtained by numerical electromagnetic modeling,^{11-14, 35-37} from which ratios of the peak local SAR to the total power can be derived. These are, however, anatomy dependent. In practice, the total deposited power may be used in conjunction with numerical electromagnetic models to provide estimated local SAR values.^{17, 35-40}

[0046] In the Philips scanner, because of losses in the cables, RF coil and other transmit chain components, the power reaching the imaging subject in the Philips scanner was less than half the power supplied by the RF transmitter. The smaller power loss for the Siemens scanner indicates the use of lower loss components. Moreover, both scanners' whole-body SAR estimates reported to the scanner operator seem conservatively overstated. While this may provide an extra safety margin for RF exposure, it nevertheless means that scanner SAR values are not reliable for specifying RF exposure when testing the MRI safety of peripheral, implanted and interventional devices.^{3, 20} The overestimate may also limit high-SAR pulse sequences, forcing unnecessary reductions in duty cycle or pulse power that increase scan time and/or compromise efficiency.

[0047] Some embodiments of the current invention can provide a versatile approach to accurately measure, in real-time, the total RF power deposition during MRI, independent of the scanner. We have used our real-time power monitoring system to demonstrate deficiencies in commercial scanner reported RF SAR values in some examples. Some embodiments can be used to monitor regulatory compliance, SAR dosimetry, evaluation of scanner function following burn injuries and for setting RF exposure levels during device safety testing. In addition, applications of the current invention are not limited to MRI, but can be used for measuring RF power in other applications including radar, medical RF diathermy, RF ablation systems, and RF telecommunications systems.

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[0049] The embodiments illustrated and discussed in this specification are intended only to teach those skilled in the art how to make and use the invention. In describing embodiments of the invention, specific terminology is employed for the sake of clarity. However, the invention is not intended to be limited to the specific terminology so selected. The above-described embodiments of the invention may be modified or varied, without departing from the invention, as appreciated by those skilled in the art in light of the above teachings. It is therefore to be understood that, within the scope of the claims and their equivalents, the invention may be practiced otherwise than as specifically described.

WE CLAIM:

1. A device with at least one channel for measuring high dynamic range, radio frequency (RF) power levels over broad-ranging duty cycles, comprising:

a power sensor circuit comprising at least one logarithmic amplifier;

at least one directional RF coupler electrically connected to said at least one power sensor;

at least one RF attenuator electrically connected to said at least one RF coupler; and

at least one sampling circuit electrically connected to said at least one RF attenuator and said at least one RF coupler,

wherein said at least one sampling circuit performs analog-to-digital conversion of electrical signals received to provide digital signals for measuring the RF power level in the at least one channel.

2. The device of claim 1, further comprising a computer configured to communicate with said at least one sampling circuit to receive said digital signals.

3. The device of claim 2, further comprising a display configured to communicate with said computer.

4. The device of claim 3, wherein said computer is further configured to calculate measured peak power from said digital signals in real time and said display is configured to communicate with said computer to provide real-time display of said measured peak power.

5. The device of claim 4, wherein said computer is further configured to calculate measured average power from said digital signals in real time from said at least one channel, and said display is configured to communicate with said computer to provide real-time display of said measured average power from said at least one channel.

6. The device of claim 1, wherein the at least one channel is more than one channel, wherein each channel comprises a power sensor circuit comprising a logarithmic amplifier connected to a directional RF coupler electrically connected to a RF attenuator electrically connected to at least one sampling circuit, and

wherein each said sampling circuit is electrically also connected to each RF attenuator to provide multichannel RF measurements.

7. The device of claim 6, wherein the at least one channel is four channels.

8. The device of claim 1, wherein said high dynamic range, low duty cycle RF power levels are produced by a magnetic resonance imaging (MRI) system and said device is MRI compatible.

9. The device of claim 8, wherein said device is adapted for monitoring RF exposure of a subject in said MRI system,

wherein said MRI system operates in a frequency range of 1 MHz to 400 MHz.

10. The device of claim 9, further comprising a Q-hybrid transducer.
11. A method of monitoring radio frequency (RF) exposure proximate an RF emitting device, comprising connecting an RF monitoring system according to claim 1 to an RF power source of said RF emitting device.
12. The method of claim 11, wherein said RF emitting device is a magnetic resonance imaging (MRI) system.
13. The method of claim 11, wherein said RF power source is an RF coil of an MRI system.
14. The method of claim 11, wherein said RF emitting device is at least one of a radar system or a telecommunications system, or a medical RF diathermy system, or a RF ablation system..

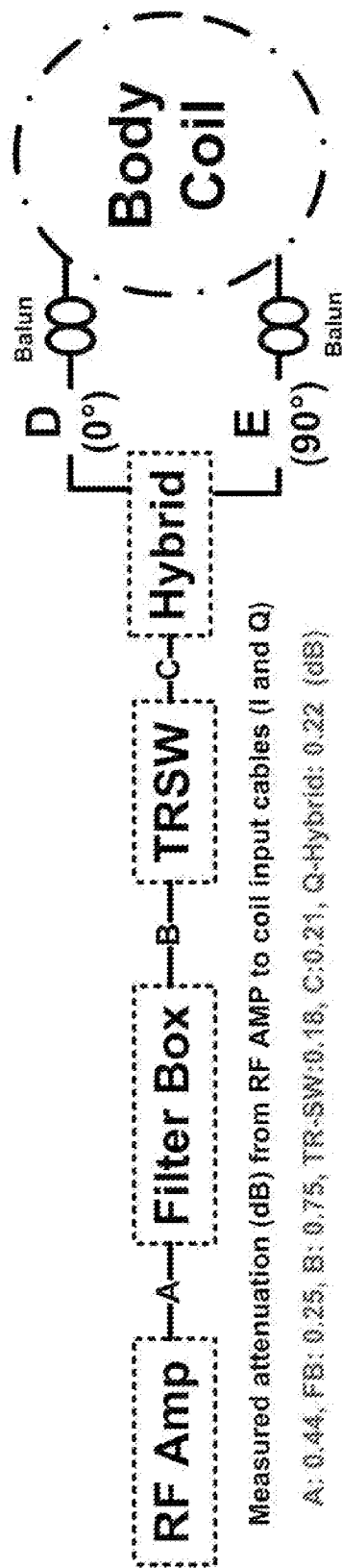


FIG. 1

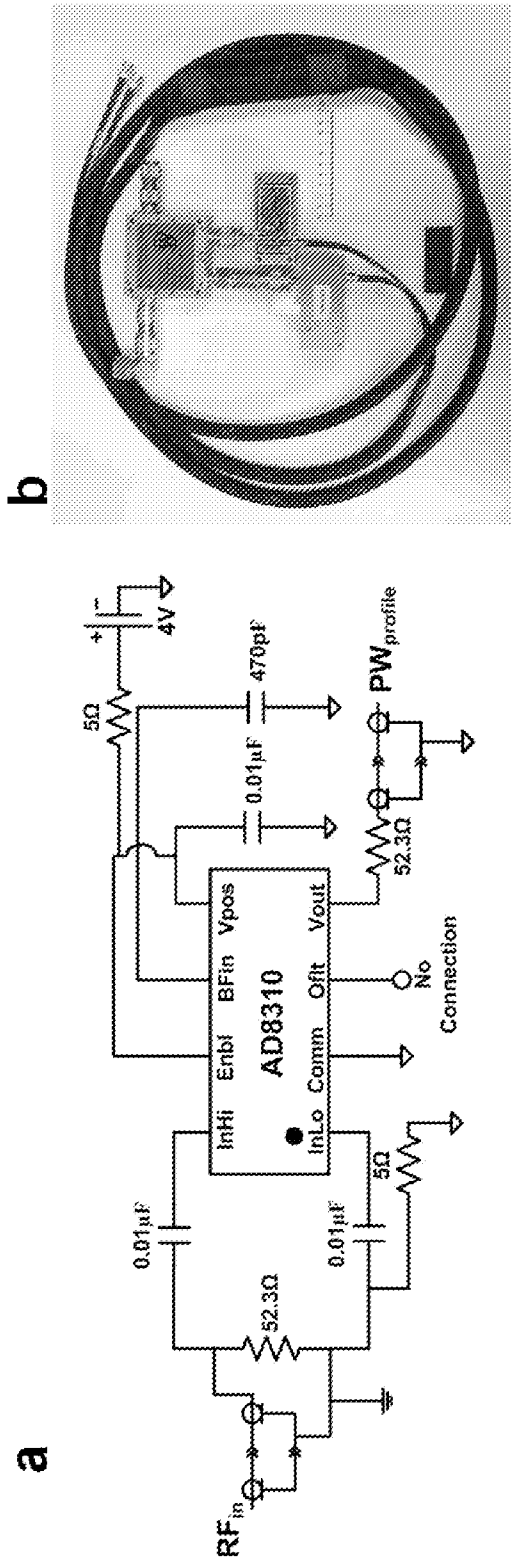


FIG. 2A

FIG. 2B

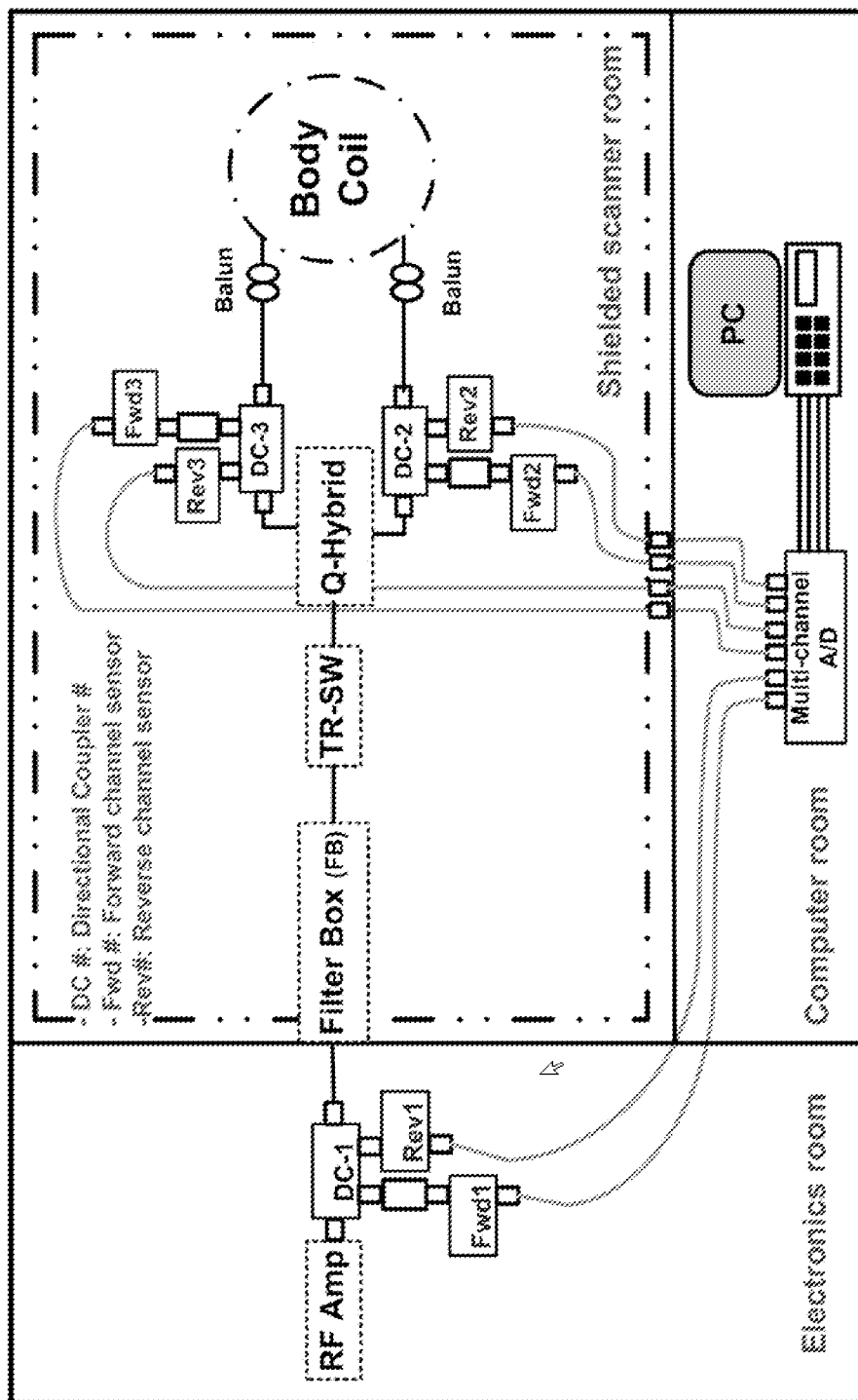
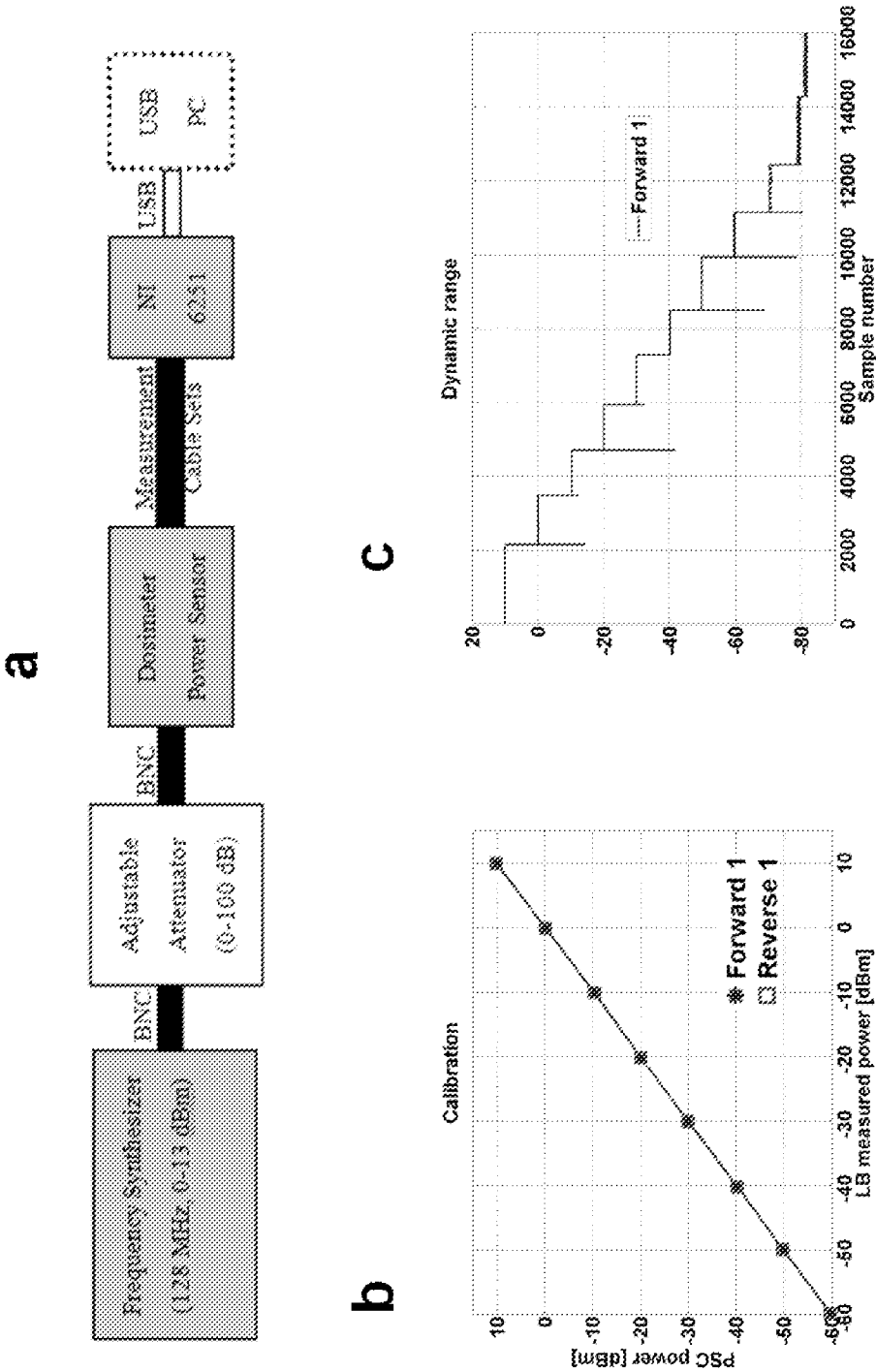


FIG. 3



FIGS. 4A-4C

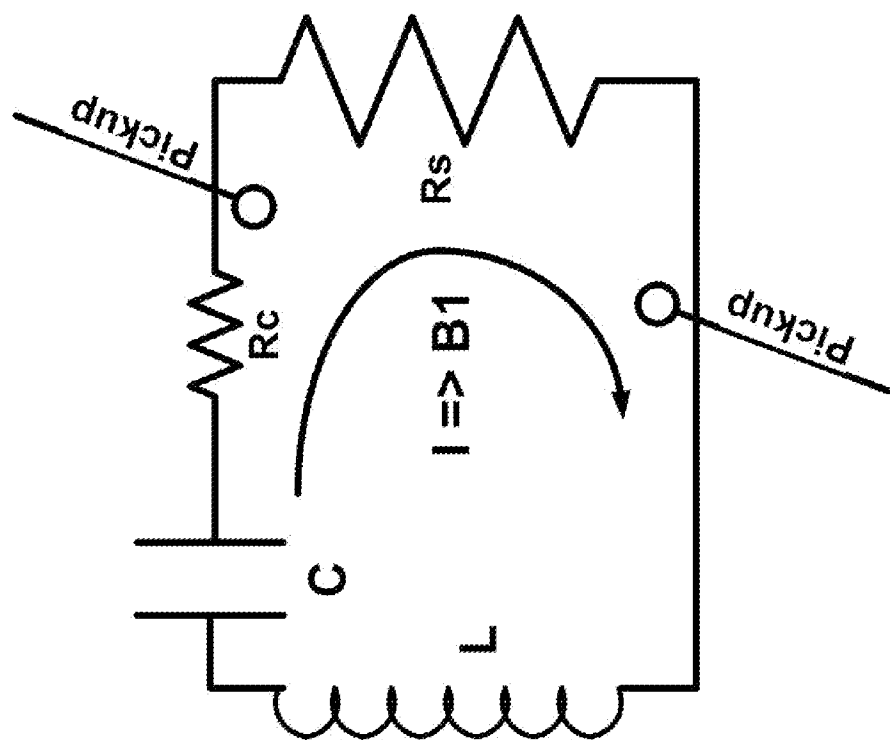


FIG. 5

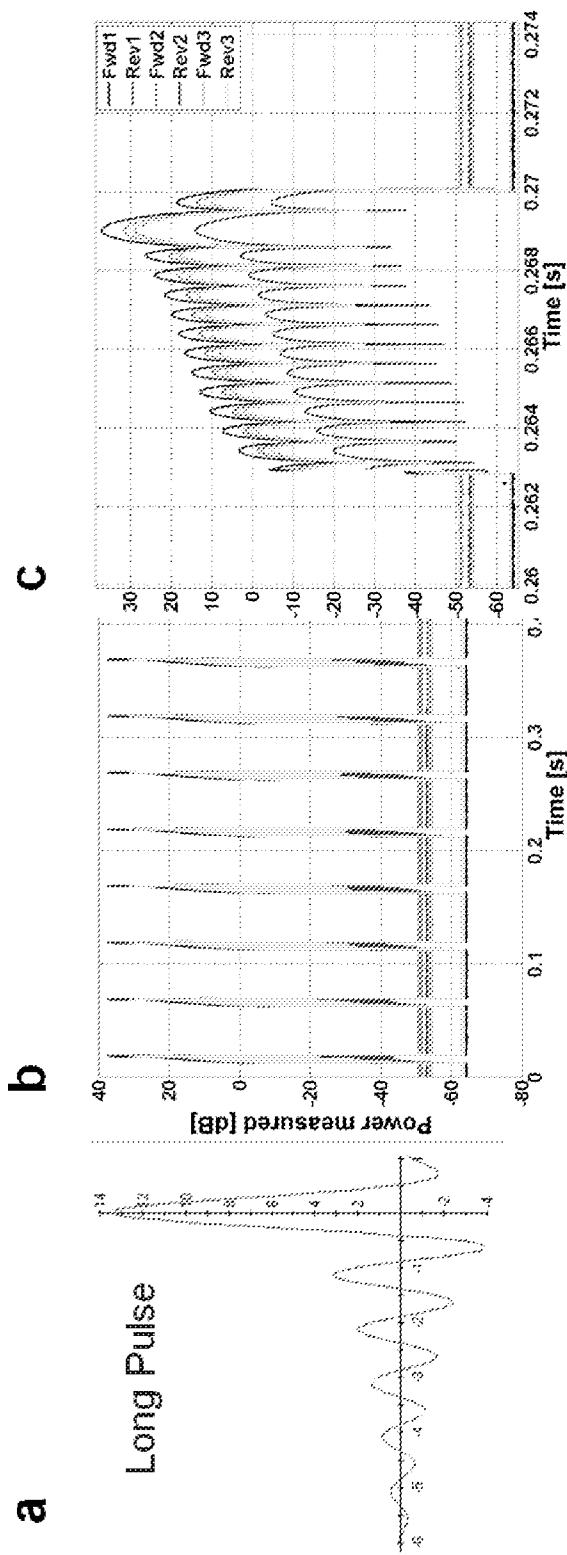
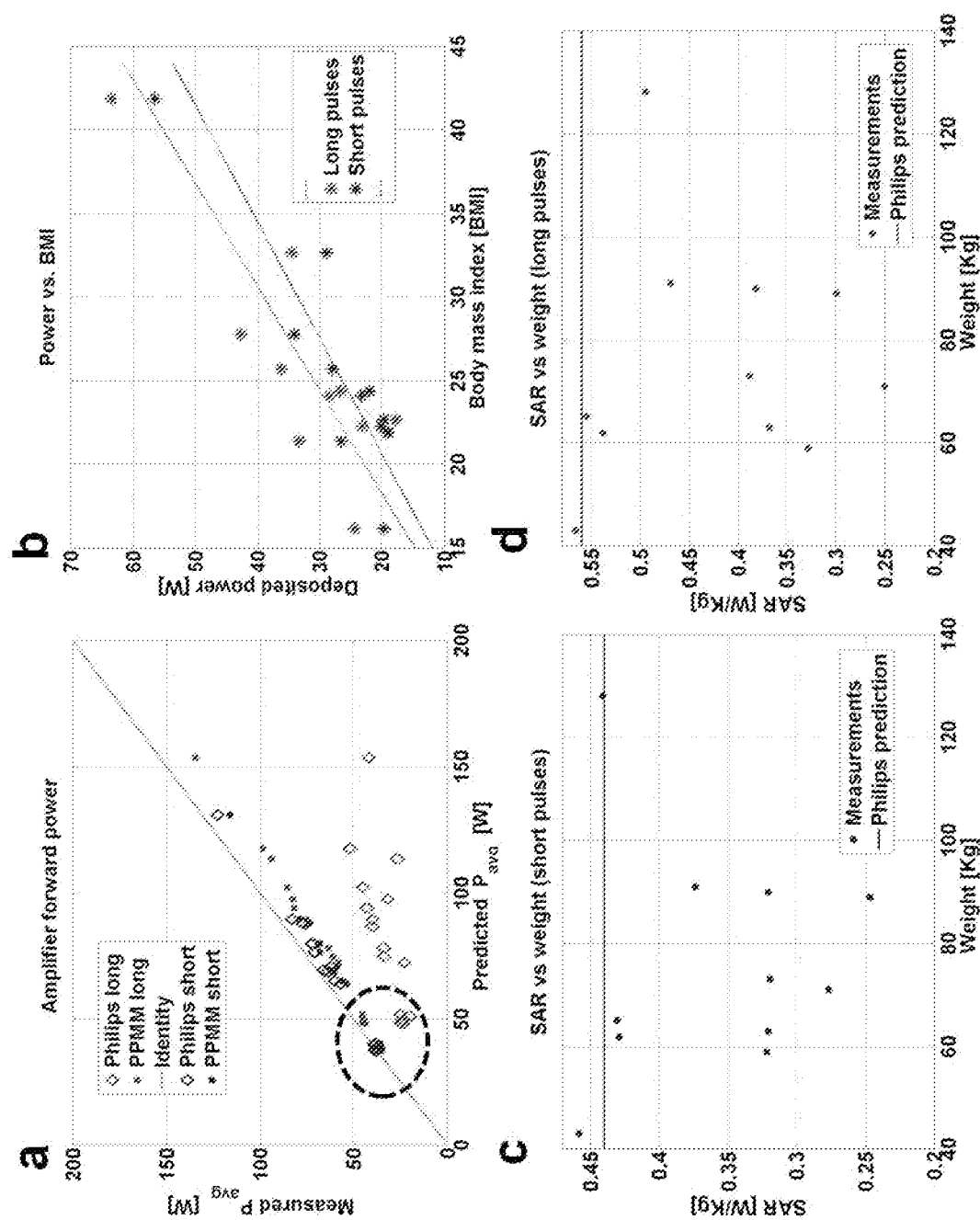


FIG. 6A

FIG. 6B

FIG. 6C



FIGS. 7A-7D

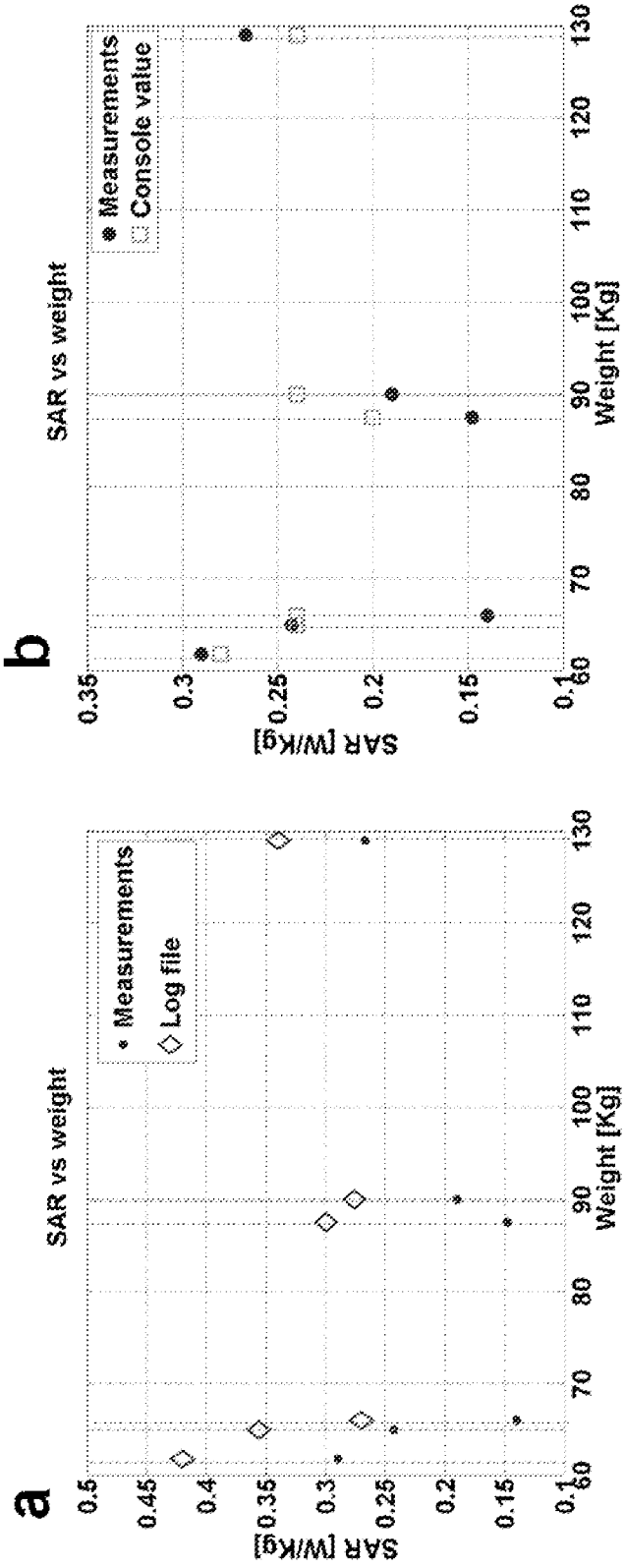


FIG. 8A

FIG. 8B