skope

CLIP-ON CAMERA
MANUAL

Revision 2016a

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1. IMPORTANT NOTES – READ BEFORE USE

Please read these notes as well as the entire manual in order to prevent harm to users and subjects as well as damage to the MR system, the Acquisition System, and connected RF front ends such as the camera.

The use of the Clip-on Camera in conjunction with high power RF pulses is only allowed with RF pulses at the ^{1}H Larmor frequency at the field strength the Clip-on Camera is specified for. High power RF pulses at other frequencies must not be applied while the Clip-on Camera is inside or in the vicinity of the MR scanner bore.

This Clip-on Camera and the resulting data must not be used for clinically relevant decisions.

DISCLAIMER

This is an investigational device.

Only trained users shall install the Clip-on Field Camera (and the corresponding acquisition system), use, and handle it. The device is connected to and used with the MR system at the user's own risk and liability for the MR system, its surrounding installations, as well as people, volunteers, and patients involved.

Skope Magnetic Resonance Technologies asks the user of the system to take explicit notice of the risks involved with this system present in the MR system during high power RF pulses. The installation and usage of the Clip-on Camera and its back end requires experts trained in the art of RF engineering and safety, establishing state of the art safe operation for the MR scanner, the Clip-on Camera and – if involved – the subject.

Skope Magnetic Resonance Technologies does not take any responsibility or liability for damages, harm, loss of data or similar incidents that are in direct or indirect relation to the usage, connection or presence of any of its devices. MR sequences or particular implementations thereof can be subject to intellectual property of one or several parties.

In accordance to investigational device usage practice, clinical evaluation of this device requires:

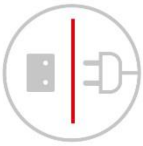
- *An Investigational Device Exemption (IDE) approved by an institutional review board. If the study involves a device posing significant risk, the IDE must also be approved by FDA;*
- *Informed consent from all volunteers and patients;*
- *Labeling 'for investigational use only';*
- *Monitoring of the study and;*
- *Required records and reports.*

The content of this document can change without notice.

READ PRECAUTIONS THOROUGHLY BEFORE USE

Avoid High Power RF Transmission Pulses other than on the ^{1}H Frequency
The unit or any components of it must not be exposed to any high power RF transmission pulses at frequencies other than the ^{1}H Larmor frequency at the field strength the Clip-on Camera is specified for.

Do not use during standard MRI Exams
The device or any parts of the device must not be used, remain close or be connected to the scanner during MRI exams on humans or living animals, if no dedicated field monitoring examination is being performed.



Disconnect when not in use
The device should not be powered and should not be connected to the MR system, while not being directly supervised by a trained expert.
Always disconnect the trigger and sync lines and power down the device when leaving the scanner area or when the measurements are paused or finished. Do not leave any connection to the scanner during investigations that do not involve field monitoring.

Avoid improper Connections
Make sure to establish all connections correctly. Wrong connections can harm the device irreversibly.

Temperature Range
The device must be stored within the temperature range of +16°C to +26°C. Transport of the device must be at temperatures in the range of +13°C to +33°C. Do not expose to direct sunlight.

Handle with Care

Protect the device against strong mechanical forces, torques, shocks and vibrations. Do handle the connectors and cables with care, avoiding excessive mechanical forces, bending, and torques being applied to any part during manipulation, measurement, and storage.

Wipe with a dry or damp cloth; prevent any liquid and moisture from entering the Clip-on Camera housing.

Do not operate the system when damaged, especially in the case of (partially) ruptured cables and loosened connectors.

ESD Protection

Protect the device from electrostatic discharges (ESD protection). Do not touch any conductive surfaces while not being grounded.

Never leave Ports open

Never leave one or several of the ports open (e.g., SMA connectors on the Clip-on Camera). Improper termination or other sources of RF reflections will harm the power amplifier. Stop the measurement if a field probe is not operating properly or shows unusually low signal. If a field probe shows a strong RF mismatch or wrong tuning it can be temporarily replaced by a (non-magnetic) 50 Ohm termination.

Do not connect other devices such as NMR coils or similar to the outputs of the Clip-on Camera connection box.

Do not cover Cooling Slots

Do not block any of the venting slots, nor reduce the airflow by objects in close vicinity. Overheating of the electronics may degrade its performance and reduce its lifetime.

Check Signs of Malfunction

If any signs of malfunction or damage occur, do not continue to operate the device, since serious harm or further damage might result.

This holds particularly for probe heads with deteriorating signal or signs of mechanical damage of the casing, the cabling, or the connectors.

Please follow the advice in the troubleshooting section and contact Skope for further support.

2. HARDWARE SPECIFICATIONS

Ambient Conditions	
Working ambient temperature range	16 to 26°C
Storage ambient temperature range	16 to 26°C
Transport ambient temperature range	13 to 33°C
Do not expose to direct sunlight	
Maximum magnetic field exposure	12 T

NMR Field Probes (typical)	
Coherence lifetime at 3T and a main field inhomogeneity < 0.1mT/m	50 ms (typical)
Minimum repetition time (depending on NMR field probe T_2 value)	3 x coherence lifetime (typical)
$\mathrm{SNR} \cdot \sqrt{\mathrm{BW}}$ (the sensitivity at FID start)	65'000
Achievable k_{max}	±7800 rad/m

Field Probe T/R Connectors (SMA on Active Electronics of Clip-on Camera)	
Maximum reflection	-10 dB
Maximum output peak power	4 W
Maximum average power	0.1 W
Maximum input power (via RX connector)	+20 dBm
Maximum DC voltage	±1 V

Voltage Supply	
Minimum input voltage	5.5 V
Maximum input voltage	7 V
Maximum current draw (after startup)	2 A

Trigger Inputs (Trig, Data)	
Levels	0 V low, +3.3 V high (excitation active high)
Absolute Maximum	-0.1 V to +4 V
Maximum Input AC power (external)	-6 dBm

TX Input	
Maximum AC input power	
in probe frequency band	+6 dBm
at all other frequencies	-20 dBm
Maximum DC voltage	5 V
Maximum transmit duty cycle	10%

Receive Lines (RX 1-16)	
Maximum Input AC power	-6 dBm
Maximum output AC power	+20 dBm
Maximum DC input voltage	±2 V

RF front end	
TX small signal gain (TX to T/R typical)	+33 dB
RX small signal gain (T/R to RX typical)	+22 to +24 dB
RX noise figure	+1.2 dB
Minimum T/R switch transient duration	1 µs
Maximum T/R switch rate	10 kHz
Maximum transmit duration	10 µs

Physical Dimension	
Housing (w × d × h)	24 cm × 20 m × 13 cm
Cable diameter	3 cm
Cable length	1 m to 10 m

3. FUNCTIONAL OVERVIEW

This section provides an overview of the Field Monitoring System and its operation.

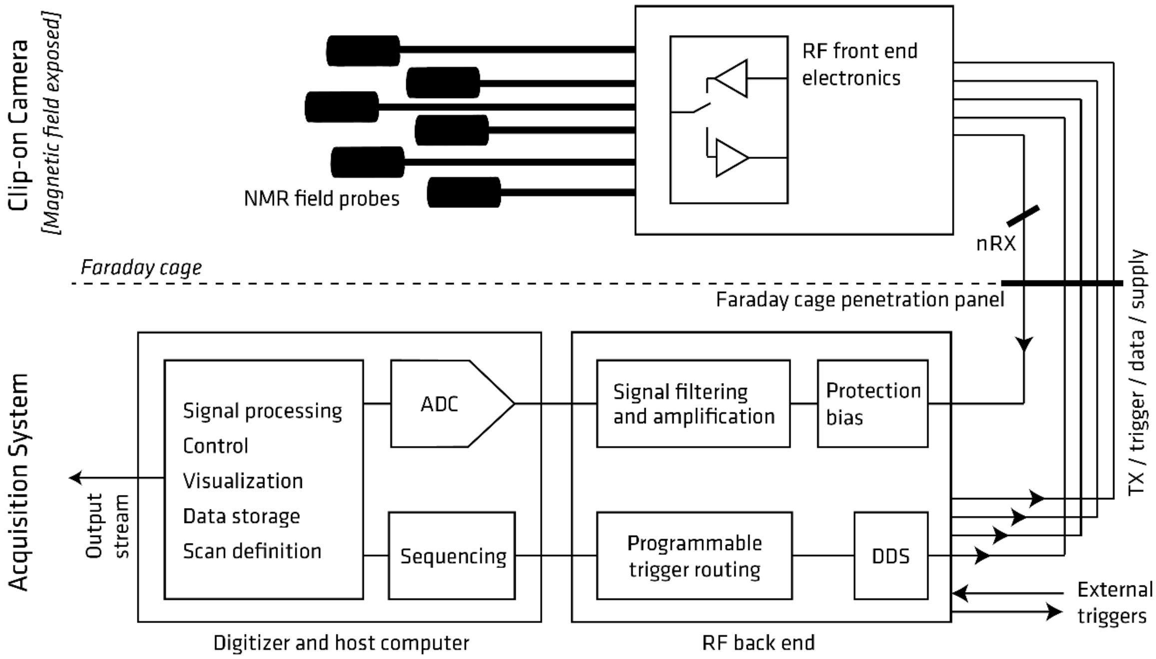


Figure 1: Schematic overview of the Clip-on Camera with Acquisition System (RF back end, digitizer and host computer, control- and visualization unit, data storage), software, triggering, and data stream.

The Field Monitoring System consists of the Clip-on Camera – containing the field probe array and the RF front end – and the Acquisition System – containing the RF back end, the digitizer and host computer, the control- and visualization unit, and data storage. While the Clip-on Camera goes into the bore of the MRI system, the Acquisition System must remain outside the 5 Gauss line and outside the Faraday cage.

4. CLIP-ON CAMERA

The Clip-on Camera (Figure 2) consists of the NMR field probes and active electronics that go into the MRI scanner bore. The active electronics encompasses transmit-receive switching, low-noise pre-amplification of the received signals, and power amplification of the transmit signal for NMR field probe excitation.

Figure 2: Clip-on Camera on a patient bed.

The field probes are ^{19}F-NMR-based sensors that are tuned for the application at a specified main magnetic field strength. The field probes are flexibly placeable, e.g., on a head-coil array. However, make sure to follow the Safety Instructions as detailed in this document. The field probes must be oriented along the axis of the scanner's main magnetic field in order to achieve the specified sensitivity and signal lifetime.

The cable bundle entering the Clip-on Camera contains 20 coaxial lines connecting to the Acquisition System. The bundle carries the 16 analog receive signals from the field probes ('RX 1-16'), supplies the necessary voltage ('Supply'), provides the RF waveform for transmission ('TX') as well as trigger and data lines ('Trig', 'Data'). Please note that the RF connections as well the RF outputs and control signal lines are sensitive to electrostatic discharge as they may occur by touching the center contact of the connection.

Since the field probes are optimized for field measurement precision, they are extremely sensitive RF detectors. Hence no external power RF transmission (excitation pulses and similar) of other than the ^{1}H Larmor frequency at the field strength specified for the Clip-on Camera must be applied by the MRI scanner, while the Clip-on Camera is inside or in proximity of the scanner bore. Therefore, experiments involving multiple nuclei must not be performed with the Clip-on Camera in place.

Neither the field probes nor the RF front end of the Clip-on Camera must be exposed to strong mechanical forces, torques and shocks, and its cable bundle must be strain-relieved during operation and storage. Please also prevent twisting of the cable bundle when rolling it up for storage or during installation.

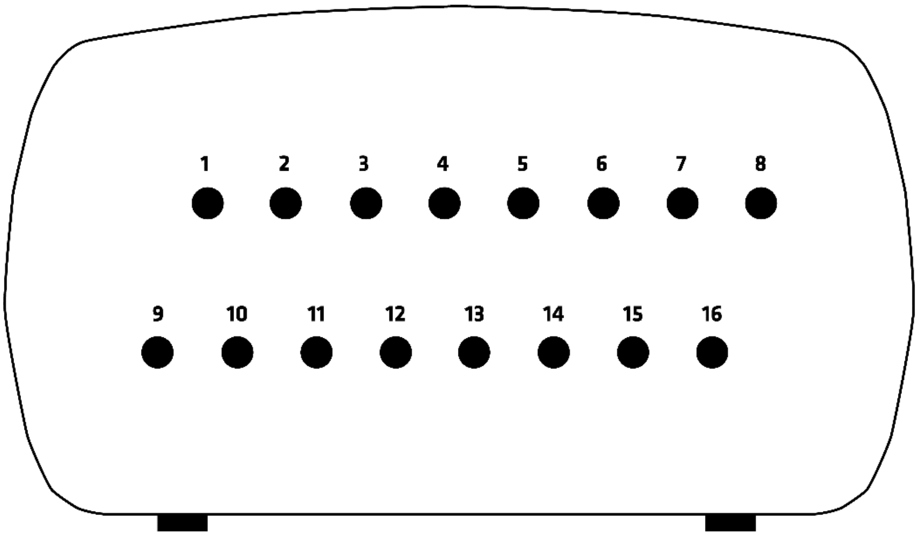


Figure 3: RF front end channel numbering

5. INSTALLATION, HANDLING, AND REMOVAL OF THE CLIP-ON CAMERA

When handling the Clip-on Camera – especially when touching conductive surfaces such as its connectors – make sure that the electrostatic charges accumulated on the human body are discharged (e.g., by touching a grounded structure).

The SMA connector nuts of the field probe cables need to be fastened with a defined torque moment. The recessed SMA connectors of the T/R ports on the RF front end must be fastened using the dedicated SMA wrench provided by Skope.

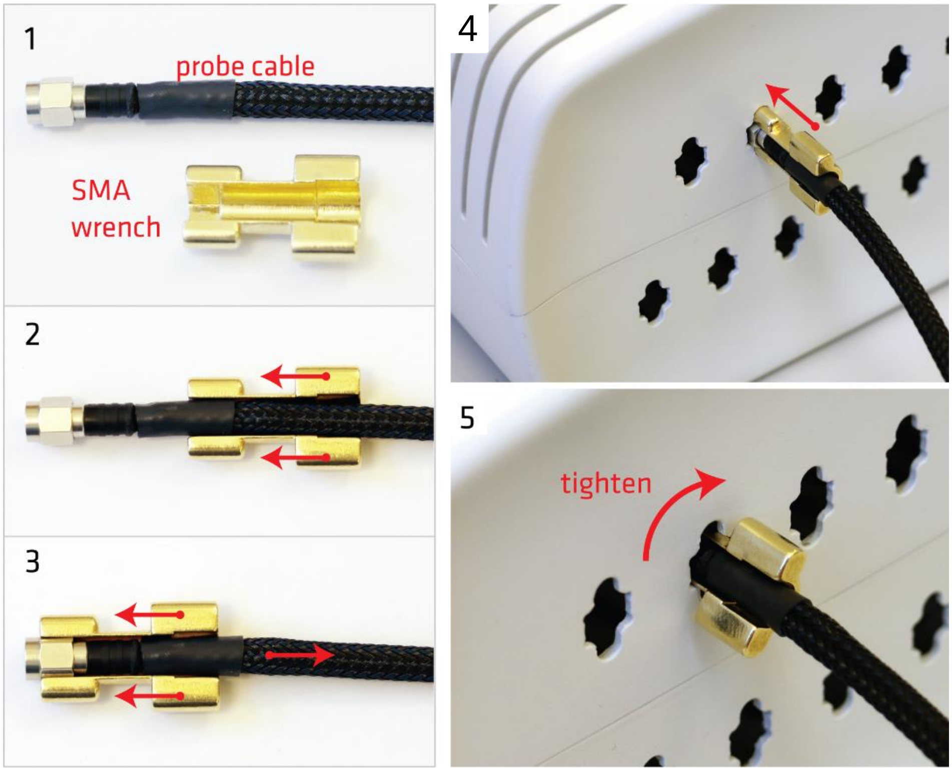


Figure 4: SMA wrench usage

Do not remove any parts of the housing of the RF front end, since it forms a core component of the shock hazard preventions.

Make sure that the circuit breakers of the digitizer and the RF back end are turned off (0) when the system is installed.

Before installing the Clip-on Camera in the MR system, ensure that the MR scanner will not emit any RF pulses at frequencies other than the ^{1}H Larmor frequency. Skope does not take on any liability for damages to the installed equipment, loss or corruption of data, or injuries that may arise from the application of such RF pulses.

Always position the Clip-on Camera (field probes and RF front end) such that their long axes are parallel to the main magnetic field axis. The field probe heads need to be placed remotely from sources of static magnetic field perturbations (strongly paramagnetic or even ferromagnetic materials). Bear in mind that nearby sources of gradient-induced eddy currents (RF shielding, connectors, larger conductive structures, etc.) can generate dynamic field patterns of spatially very high order that might not be resolved by the field probe array of the given Clip-on Camera.

The field probes of the Clip-on Camera should be placed around the sensing region of interest, but as close as possible to the isocenter of the MR system for meaningful operation. The distribution of the field probes will determine the sensitivity to different spatial field patterns.

When mounting the Clip-on Camera on the patient support, make sure that the cable bundle is neither twisted nor excessively bent. The cable bundle must be strain-relieved in order to prevent undesired motion of the unit and damage to the connections. Please make sure that the cables can move freely when rolling the patient support into or out of the bore. Ensure that the camera and the cables do not get pinched, blocked or torn by the patient support movement. Make sure that none of the venting slots of the Clip-on Camera are blocked, since overheating of the electronics degrades its performance, can reduce its lifetime, and can cause direct harm to the system.

Before making any connection to the Faraday cage or to the RF back end, make sure that the RF back end is turned off, using its circuit breaker.

Connect the 16 receive lines ('RX 1-16') coming from the camera to the Faraday penetration panel and make the corresponding connection on the outside of the Faraday cage to the Acquisition System (RF back end). Then connect the connectors for 'TX', 'Supply', 'Trig', and 'Data'. Please make sure to prevent wrong connections – paying particular attention to the 'TX' and 'Supply' lines – since these might harm the system. Clearly and permanently labelling the connectors on the penetration panel on the inside and outside of the Faraday cage is a recommended means to prevent wrong connections.

If needed, connect the real-time trigger lines for measurement synchronization to the corresponding inputs of the Acquisition System. Please refer to the manual of the Skope Acquisition System for further information.

Roll the patient support into the magnet such that the field probe array is placed around the isocenter and prepare the MR system for the measurement.

After the hardware is set up and ready to measure, power up the Field Monitoring System by switching on the RF back end's main circuit breaker and then power up the digitizer by the corresponding mains switch. The starting sequence of the RF back end takes several seconds; the digitizer has to boot the Windows® operating system. Then launch the Skope *Scan Application* and start a first measurement for checking proper operation of the system. In this case 16 FIDs with similar lifetime and amplitude are acquired (unless the homogeneity of the static field is compromised). For measurements of highest accuracy, after the first acquired FID, a camera warm-up phase of 10 min is recommended in order to establish thermally stable operation.

Before the Clip-on Camera is removed or manipulated, the digitizer first needs to be shut down via the Windows start menu (wait until the digitizer switches off). Then turn off the power of the RF back end via the provided circuit breaker on the RF back end.

All connections to the scanner and to the Faraday cage on the side of the camera and towards the Acquisition System must be removed before the MR scanner is used again without the Field Monitoring System. Check that the RF penetration panel is again RF proof, e.g. by applying caps onto the panel connectors. It is strongly recommended to check the MRI scanner for proper operation after removal of the Field Monitoring System before scans on humans/patients are performed without the Field Monitoring System. When not performing field monitoring, do not operate the MRI scanner with humans or live animals as subjects as long as the Field Monitoring System is connected to the MRI scanner or to any of its peripherals, or as long as the Field Monitoring System is powered up and connected to the mains.

If the Field Monitoring System is not in use or not under surveillance of a trained expert, the Acquisition System and its front ends must not be turned on or connected to the power mains, and must not be connected to the MR scanner or its peripherals.

6. USE

Follow the Safety Instructions described in this document for safe use of the Clip-on Camera.

The input trigger to the Acquisition System specifies the time point of the start of the excitation of the field probes. The field probes are excited by a short (few microseconds) RF pulse. After the field probe excitation, the system automatically switches to the receive mode and acquires signal from the front end for the duration specified in the scan definition (cf. software section of the Acquisition System manual).

Consecutive field probe excitation with a repetition time (TR) below 5 times the field probe lifetime can lead to systematic errors in the phase evolution of the field probes due to NMR echoes. Please note that triggers will be ignored during an acquisition period (interleave TR · number of interleaves), cf. the software section of the Acquisition System manual.

The signals received from the Clip-on Camera are then processed, stored and prepared for visualization of the dynamic field evolution. See the software section of the Acquisition System manual for further details.

The NMR field probes in the Clip-on Camera come with a fixed tuning/matching that cannot be adjusted. Do not open the casing of the Clip-on Camera (field probes and RF front end), since permanent damage of the casing and field probes might occur. In case of single field probes showing loss in signal amplitude, quick de-phasing of their coherence, or other signs of improper operation, please stop the measurement and contact Skope immediately. Operating the Clip-on Camera with damaged field probes might cause permanent damage to other system components.

7. CALIBRATION

The positions of the field probes are best described in the coordinate system spanned by the MR scanner gradient system – rather than in Euclidean coordinates. In order to determine the field probe positions in the scanner coordinates, a calibration sequence must be run, as described in the manual of the Skope Acquisition System (software section).

If the Clip-on Camera is employed for dynamic shim characterization or to implement real-time shim feedback, it can be desirable to characterize the probes positions in "shim-coordinates". This can be performed by applying constant shim amplitudes during the acquisition of probes' FIDs with the Acquisition System (Further reading: *Real-time feedback for spatiotemporal field stabilization in MR systems, Magn Reson Med, 2014*).

For real-time applications, the real-time *Ethernet field value output queue* option of the Acquisition System can be used to interface an external program also for calibration purposes.

8. SAFETY INSTRUCTIONS

The content of this chapter is to be considered as guidelines. It is important to note that the observation of these guidelines does not ensure safe operation in every possible application; hence MRI safety expert knowledge is required for establishing safe operation.

BACKGROUND

Three types of risks have to be considered when running field monitoring experiments with a Clip-on Camera present in a MRI system that emits RF excitation pulses:

1. The conductive structures of the field probes can guide RF energy into the tissue of the subject, causing potentially harmful heating of the tissue or material close to the tissue.

2. RF energy coupled into the field monitoring system can deteriorate the field measurement and/or cause irreversible damage to the monitoring system (RF front end, RF back end, digitizer).

3. The conductive structures of the field probes and/or their driving devices interact with the MR scanner RF hardware, such that the function of the RF hardware is altered. This can either lead to a potentially dangerous situation for the subject in the scanner (if the SAR estimation of the native RF equipment is not valid anymore), or the RF equipment itself can be damaged.

The three categories of risks can be minimized by reducing the coupling of the field monitoring system to the RF transmitter. The various coupling mechanisms are shown in Figure 5; every mechanism depicted in the figure is symbolized by a number and discussed in the following.

As shown by (1) the RF field generated by the transmitter can directly couple into the field probes; this mechanism is greatly suppressed by a gradient compatible proprietary shielding of the sensors. However, this shielding is only provided if the housing of the sensor is intact and the sensor was never opened.

Mechanism (2) denotes coupling of RF currents via capacitive coupling to other conductive structures such as the transmit coil itself, receive coils, or similar. Although coil builders take great care to avoid this coupling mechanism by balanced coil constructions, this mechanism was found in certain situations to be dangerous by coupling large currents into the outer conductive structure of the field probes (‘cable shield current’).

Once such a common mode current is present, it can be easily coupled into the subject via the capacitance to conductive tissue (3). This capacitance greatly reduces with increased distance between field probes and body. However, in conjunction with inductance formed by the cable, dangerous resonances can be formed.

The cable shield current (4) can also directly cause local RF heating via the induction of eddy currents in the tissue. → Keep field probe cables at a distance of at least 1 cm from the subject or other conductive structures.

Proximity between field probe heads (5), between cables (6), or between field probe heads and cables can introduce significant capacitance between these structures. This capacitance closes a loop that the field probes cables form in conjunction with the common grounding of the RF front end. RF flux through the loop induces potentially strong currents, whose amplitude depends on loop area, orientation, and resonance (depending on the capacitance value).

The last mechanism of coupling (7) is formed by the cables connecting the RF front end and potentially present transmit-, transceive-, or receive coil (-arrays). Such coupling can lead to strong signals coupling into the electronics of the RF front end.

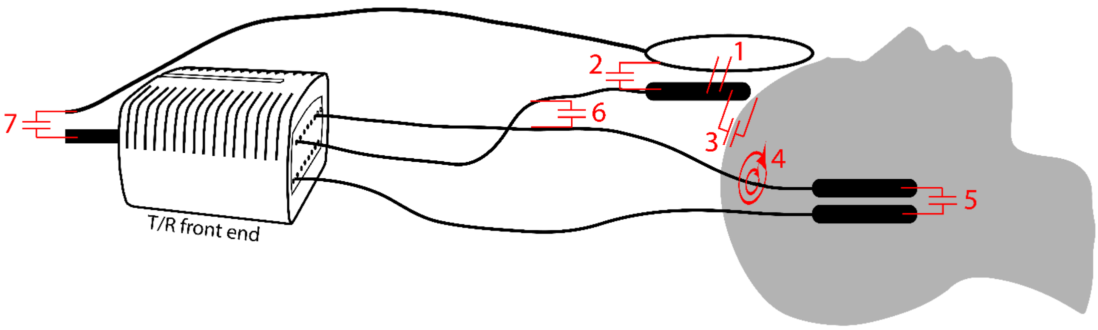


Figure 5: Mechanisms of RF coupling to field probes.

Furthermore, tuned RF traps used on MRI coils can be de-tuned and hence rendered ineffective by the (close) presence of other conductive structures.

GUIDELINES

- Before every installation, check the Clip-on Camera for its integrity. Field probes, cables, connectors or TR interface units with cracks, ruptures, damaged insulator jackets, kinked cables or other signs of malfunction cannot be considered as safe.
- Do not prolong or shorten cables or connections of field probes.
- Do not operate a Clip-on Camera at a field strength it is not specified for.
- Adhere to a minimum distance of 1 cm between the subject and any part of the field probe cables, field probe heads, RF front end. Paddings might be used to ensure this minimum distance.
- A minimum distance of 1 cm must be kept between two field probe heads, two field probe cables, or a field probe head and a field probe cable.
- Do not form loops or slings with the field probe cables.
- Neither bring field probe heads nor field probe cables close to RF current carrying structures, be they active or passive.
- Do not route cables close to RF coils or the bore liner (housing the body-coil); keep the probe heads at maximum distance to these structures. Especially the end-rings of volume resonators exhibit a strong potential to couple into and onto field probes.
- Do not bring any cable of the Clip-on Camera close to cablings of other system components, in particular not close to tuned circuits such as RF coil conductors, cable traps, etc.
- Mount the field probe heads and cables such that the subject cannot get entangled, when trying to leave the scanner. Avoid that the subject can reach the field probe cables with its arms.

SUGGESTED VALIDATION METHODS

Mount the Clip-on Camera (including the RF front end) with your setup observing the above guidelines. Connect the RF front end to the penetration panel at the Faraday cage, but do not connect it to the acquisition system. Now only connect the supply line of the acquisition system to the penetration panel (where it is connected to the RF front end) in order to power the RF front end.

The entire system should be setup as in the intended experiment whose safety is to be assessed.

A. Coupling into receive lines of the RF front end

Method 1

Given access to the RF transmit path, the coupling into the field probes can be measured using a network analyzer (VNA) or a signal generator and a corresponding recording device, such as an oscilloscope (with 50 Ω termination) or a spectrum analyzer. The test signal (emanating from the signal generator or the transmitting port of the VNA) must be fed into the transmit port of the tuned transmit coil (check that the MRI system does not detune the coil in idle mode) and the signal in the RX line of each field probe after pre-amplification (i.e., after RF front end) should be measured. Make sure that the RF front end is operative and that the SNR of the measurement is sufficient to estimate the tolerated coupling. The tolerable input power to the input of the RF front end (S_(in,Tol)) is 20 dBm, so given the maximum power of the MRI system's power amplifier (P_(Amp,Max)), the maximum tolerated coupling is:

$$S_{\mathrm{in,Tol}}[\mathrm{dBm}] = 20\mathrm{dBm} - P_{\mathrm{Amp,Max}}[\mathrm{dBm}] \qquad [1]$$

The measured coupling is elevated by the gain of the pre-amplifiers (of the RF front end) minus the cable losses of the receive lines; together they amount to about $G_{\mathrm{TRfrontend}} = 22\mathrm{dB}$. If the measurement disappears in the noise, an amplifier can be added on the transmit side; its gain ($G_{\mathrm{MeasurementAmp}}$) has to be subtracted, if it is not calibrated into the VNA. The maximum tolerated coupling ($S_{\mathrm{out,Tol,Measured}}$) as shown on the measurement device is:

$$S_{\mathrm{out,Tol,Measured}} = S_{\mathrm{in,Tol}} + G_{\mathrm{TRfrontend}} + G_{\mathrm{MeasurementAmp}} \qquad [2]$$

If using a power amplifier for this purpose utmost care has to be taken to ensure safety during the measurement. Importantly, the signal level received by the RX lines of the RF front end must reside below 10 dBm in order to prevent saturation effects that corrupt the measurement. Check that the coupling is below the tolerance level for all channels of the monitoring setup.

Method 2

The MR scanner RF source can be used to check for tolerated coupling. However, it must be ensured that the scanner reduces it output power to a priori safe levels for the Clip-on Camera in all phases of operation; this includes the test scan itself, and also potentially running preparation sequences or interleaved sequences (navigators, f_0 updates, ...).

Furthermore, the ratio between the scaled down power level and the maximum output power of the MR scanner RF source has to be known (ATT). It is recommended to attenuate the input of the power amplifier by $\mathrm{ATT} = 30$ - $40\mathrm{dB}$. To measure the instantaneous peak output power on the RF front end output receive lines ($\mathrm{P_{TRout,Peak}}$) (in powered-up receive operation during the test scan with reduced peak power) one can use either a 50 Ω terminated oscilloscope that covers the RF transmission frequency, or a spectrum analyzer able to resolve the RF pulse. In order to ensure that the peak input power into the RF front end RX input ($\mathrm{P_{TRin,Peak}}$) does not exceed the maximally tolerated 20 dBm, two checks need to be performed:

1) For the measurement to be valid, the linearity of the RF front end amplification needs to be guaranteed. I.e., in the actual measurement setup and with the used ATT, the following must apply:

$$\mathrm{P_{TRout,Peak}} < 10\mathrm{dBm} \qquad [3]$$

2) For the RF front end electronics to be safe, it cannot take more than 20 dBm at its input ($\mathrm{P_{TRin,Peak}}$) once the MR scanner RF source outputs its maximum power ($\mathrm{P_{Max}}$).

$$\mathrm{P_{TRin,Peak}}\ @\mathrm{P_{Max}} < 20\mathrm{dBm} \qquad [4]$$

In other words, during the test measurement with a given ATT, the power measured at the RF front end output ($\mathrm{P_{TRout,Peak}}$), i.e. after amplification by the RF front end ($\mathrm{G_{TRfrontend}} = 22\mathrm{dB}$), must satisfy:

$$\mathrm{P_{TRout,Peak}} < 20\ \mathrm{dBm} + \mathrm{G_{TRfrontend}} - \mathrm{ATT[dB]} \qquad [5]$$

B. Ensuring normal operation of RF transmit and receive coils

The goal of the following procedures is to ensure that the RF transmission devices operate safely, and as intended and validated by the manufacturer. Influencing an RF coil by an additional resonant structure can change the performance of the RF coil and make the scanner's safety measures ineffective.

First, acquire B1+ maps and receive coil sensitivity maps without the Clip-on Camera present. The acquisition must encompass the entire volume exposed to the RF field and a phantom that closely matches the situation with the subject inside the bore should be used. Standard procedures for this purpose can be found in the ASTM standards (F 2182 – 02a).

Alternatively, low flip angle, low saturation image acquisitions can be used. In this case make sure, that the power RF power settings remain unchanged between the measurement with and without the Clip-on Camera present.

Then enter the Clip-on Camera and place the field probes as intended for the experiment with the subject-emulating phantom. Acquire the B1+ and sensitivity maps again and compare them to the previous result.

In case of critical deviations, the positioning of the field probes must be reconsidered, changing the distance to the RF coils and conductive structures. For following types of deviations should be checked in particular:

- Strong overall drop of coil efficiency (>10% reduction of overall B1+ per square root of unit power).
- Overall gradients in the strength of RF coverage (sensitivity gradients) hint at a partial de-tuning of a (volume-) coil.
- Local shadings/hyper intensities of transmission/reception fields close to the field probes and/or to local receive coils hint at strong RF currents running on the field probes as well as problems with receive coil de-tuning during transmission.
- Signal obtained from regions along the field probe cables, where no (or at most very weak) signal could be acquired without the Clip-on Camera, hint at strong currents running on the probe cables.

Especially the cables leading from the RF front end to the Faraday cage need to be checked for cable currents by an RF magnetic field sensor or a carefully operated pick-up loop. If these cable currents turn out to be strong, cable routing can be adjusted, or an additional trapping circuit can be added.

Make sure that the cables leading from the RF front end to the Faraday cage are never routed along the subject.

C. Ensuring subject safety with temperature measurements

If the NMR active field distributions of the RF coil (array) remains unchanged when adding the Clip-on Camera (as discussed in the previous point), the MR scanner power validation is ensured to operate safely (i.e., according to the manufacturers proceedings).

To ensure subject safety, also following point needs to be considered: not all RF fields that deposit power to the tissue are coupling to the nuclear magnetization. Hence it is advised to perform validations of the temperature rise according to ASTM and FDA guidelines during high RF duty cycles with the Clip-on Camera installed as intended in the experiment. The temperature rise found during 15 min must not exceed 3°C even at the most critical positions. These positions in the conductive tissue are typically close to the field probe heads and cables. Also the Clip-on Camera must be checked after the heating phase if any parts have strongly heated up. In particular, the field probe cables and the housing of the RF front end must be checked.