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ORIGINAL ARTICLE/ARTICLE ORIGINAL

Spatial localization of EEG electrodes

Localisation spatiale des électrodes EEG

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Spatial localization;
Magnetic Resonance Imaging, MRI

Abstract

Aim of the study. — An important goal for EEG-based functional brain studies is to estimate the location of brain sources that produce the scalp-recorded signals. Such source localization requires locating precisely the position of the EEG sensors. This review describes and compares different methods that are used for localizing EEG sensors.

Results. — Five different methods have been described in literature. *Manual methods* consist in manual measurements to calculate the 3D coordinates of the sensors. *Electromagnetic* and *ultrasound* digitization permit localization by using trade devices. The *photogrammetry* system consists in taking pictures of the patient's head with the sensors. The last method consists in directly localizing the EEG sensors in the *MRI* volume.

Discussion and conclusions. — The spatial localization of EEG sensors is an important step in performing source localization. This method should be accurate, fast, reproducible, and cheap. Currently, electromagnetic digitization is the most currently used method but MRI localization could be an interesting way because no additional method or device needs to be used to locate the EEG sensors.

MOTS CLÉS
Électro-encéphalogramme, EEG ;
Localisation de source ;
Capteur EEG ;
Localisation spatiale ;
Imagerie par résonance magnétique

Résumé

But de l'étude. — Grâce à l'enregistrement des courants électriques de surface, l'EEG permet d'estimer la localisation des générateurs corticaux à la source de cette activité. Pour réaliser une telle localisation de source, il est nécessaire de repérer précisément la position spatiale des capteurs EEG. Cette revue décrit et compare cinq méthodes différentes de repérage qui ont été rapportées dans la littérature.

Résultats. — La *méthode manuelle* consiste à mesurer manuellement la position des électrodes puis à calculer leurs coordonnées en 3D. Différents appareillages utilisant notamment des *ondes électromagnétiques* ou *acoustiques* ont été développés et commercialisés dans ce but. Le système de *photogrammétrie numérique* consiste à calculer la position 3D des électrodes à partir de photos numériques de la tête du patient avec les électrodes en place. La dernière

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méthode consiste à utiliser *l'IRM* pour le repérage direct des capteurs dans l'espace anatomique du sujet.

Discussion et conclusions. — La localisation spatiale des capteurs EEG constitue une étape essentielle pour estimer précisément la position des générateurs corticaux de l'activité EEG de scalp. Elle se doit donc d'être rapide, précise, reproductible et peu onéreuse. Actuellement, la numérisation électromagnétique est la méthode la plus couramment utilisée mais la localisation en IRM est une technique prometteuse car elle ne nécessite pas d'appareillage supplémentaire.

Introduction

Scalp recorded electroencephalography (EEG) is a non-invasive technique for studying electrical activity of the brain with a high temporal resolution. However, EEG data are difficult to correlate with anatomy because the underlying cortex mainly generates the scalp recorded electrical activity; this makes it difficult to identify deep generators (Gavaret et al., [4]). Source localization techniques combined with MRI make three-dimensional (3D) representations of electrical generators possible inside the anatomical space of the patient. Three steps are required to achieve this goal. Firstly, these electrical fields must be modeled with an equivalent current dipole (ECD) or with a distributed source model (LORETA, Minimum Norm, EPIFOCUS). Secondly, a head model, which includes the electromagnetic (permeability and conductivity) and geometrical (shape) properties of the head volume, is generated thanks to the segmentation of MR images. Thirdly, in order to localize the anatomical origin of electrical events, the electrical activity must be co-registered in the anatomical space of the patient. This co-registration of anatomical (MRI) and functional (EEG) data relies on the 3D localization of the EEG electrodes that are placed on the patient's head.

Five different methods are found in literature. The first one relies on manual measurement [3,9]. The second, and most currently used method, relies on the electromagnetic digitizers [7,9,15]. Other authors propose alternative techniques: MRI localization of electrodes [1,8,12,16], geodesic photogrammetry system (GPS) [11,14], and ultrasound digitization [13].

Description of methods

Manual methods

Several manual methods for 3D localization of EEG electrodes were described in the literature.

The first one is called ''direct measurement'' [3] and consists in measuring with calipers the position between each sensor and fixed landmarks (nasion, left and right pre-auricular points). These measurements enable calculation of Cartesian coordinates for each electrode that has been placed on the head (Figure 1, adapted from De Munck JC). In this approach, the electrode is modelled by a point, which represents its center of gravity.

In order to find the 3D coordinates of the electrode (M), the distances 2b, d1, d2, d3 and c are measured. The following system of equations gives the Cartesian coordinates of the electrode:

$$d1=\sqrt{\left((x-a)^2+y^2+z^2\right)}$$

$$d2=\sqrt{\left(x^2+(y-b)^2+z^2\right)}$$

$$d3=\sqrt{\left(x^2+(y+b)^2+z^2\right)}$$

$$\Longrightarrow \begin{cases} x=\left(2a^2-2b^2-2d_1^2+d_2^2+d_3^2\right)\div 4a \\ y=\left(d_3^{\,2}-d_2^{\,2}\right)\div 4b \end{cases}$$

$$z=\pm\sqrt{\left(d_2^{\,2}-x^2-(y-b)^2\right)}$$

The second method consists in measuring inter-electrode distances. Measurements are also performed using calipers. This technique assumes that the EEG electrodes are positioned in a defined configuration corresponding to the 10—20 or 10—10 International System [2,5,10]. Five imaginary planes are defined and several distances between each electrode are measured in order to estimate the Cartesian coordinates of the electrodes (Figure 2 and Figure 3, adapted from Chatrian et al., 1985).

The number of measurements is considerably reduced with this method. For example, to locate 64 electrodes, only 14 measurements of inter-electrode distances and nine additional measurements of distances between reference electrodes (like T7, FPz and T8) and fiducial landmarks (nasion, left and right pre-auricular points) are to be performed [9].

The advantages of both manual methods are that they do not require specific materials and, consequently, are of low cost. The direct method enables locating the electrodes regardless of the positioning system (10—10, 10—20, etc). The second method relies on both assumptions of a given head geometry and accuracy of electrode positioning according to the 10—20 system, which might make it not as accurate as the direct method. With these methods, the electrode coordinates are directly located in the fiducial system, which is defined by so-called fiducial points on the head surface (nasion, left and right pre-auricular points). Moreover, the calcu-

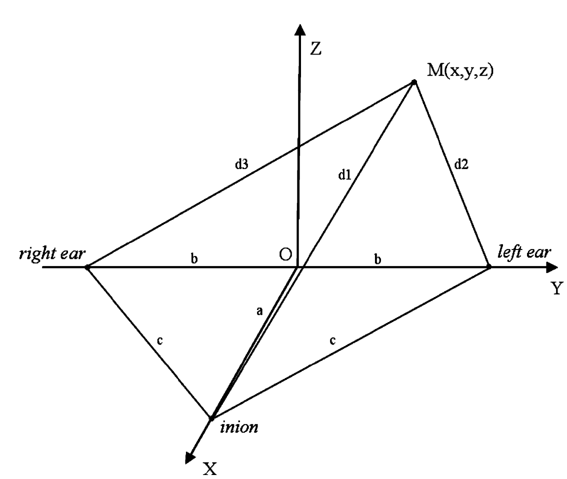

Figure 1 Manual determination of the electrode position (M).

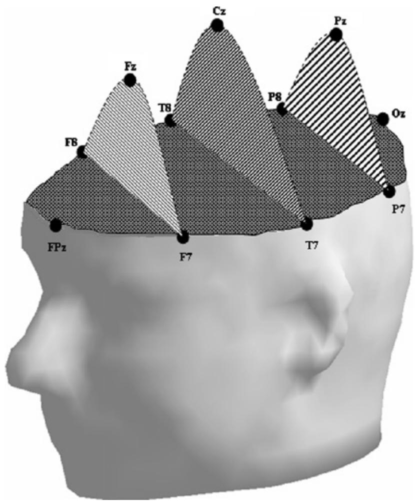

Figure 2 Five imaginary planes defined by:(1) F7-Fz-F8, (2) T7-F7-FPz-F8-T8, (3) T7-Cz-T8, (4) T7-P7-Oz-P8-T8, (5) P7-Pz-P8.

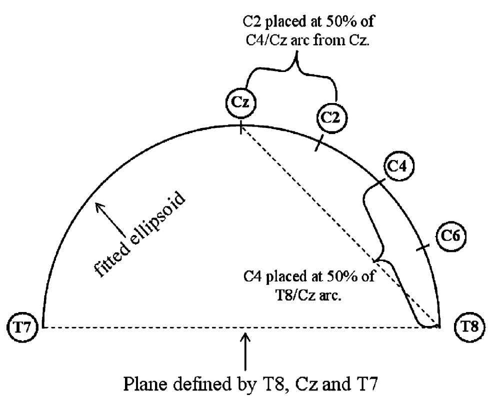

Figure 3 Estimation of 10/10 standard electrode position based on 10/10 standard logic applied to the fitted ellipsoids.

lated coordinates of the electrodes can be used without further mathematical transformations.

The disadvantages of these methods are that they are long and fastidious, due to the large number of measures. Moreover, these manual techniques are subject to non-negligible human errors and thus, cannot be used in high resolution EEG.

Electromagnetic digitization: The Fastrack system

The Fastrack system (Polhemus, Colchester, United States) is a 3D system, which uses a magnetic field to localize EEG electrodes. The system has a transmitter device that produces the electro-magnetic field and simultaneously constitutes a geographical reference for the positioning and orientations of the receivers. Three receivers are placed on the patient's head to carry out measurements. This permits head motion during the digitization process (Figure 4). Electrode position is then digitized using a pen-shaped device with a receiver coil assembly built inside (the so-called stylus) [9].

This system also enables digitization of the patient's face (nose, eyes and lips), which can improve EEG—MRI co-registration. This technique is currently the reference method to localize EEG electrodes [1,7,9]. The advantages of the Fastrack system are its reasonable accuracy and its speed of localization. Indeed, the time to digitize 64 electrodes is about ten minutes and the accuracy about eight millimeters, according to the manufacturer's data. However, individual point measurement is error-prone, as accurate mechanical positioning of the stylus must be repeated many times. A second disadvantage of this system is that the digitization mechanism is very sensitive to environmental conditions (temperature, humidity, magnetism, electric fields, etc) and so very difficult to use in a clinical setting. Besides, this system gives 3D Cartesian coordinates, which are of little use without further transformations. Therefore, performing source localization with the Fastrack system requires additional software, which makes the electromagnetic system actually very expensive.

Ultrasound digitization

Using an ultrasound digitization device (Zebris, Tübingen, Germany), 3D Cartesian positions are estimated by measuring the time it takes for a sonic impulse to travel from a sound generator (cursor or stylus) to a receiver (microphone) as illustrated in Figure 5. This method is sensitive to several environmental factors. Indeed, the speed of sound through air depends on both ambient temperature and humidity. Additionally, both electromagnetic and ultrasound methods require digitizing each point individually, which is time consuming for both operator and subject.

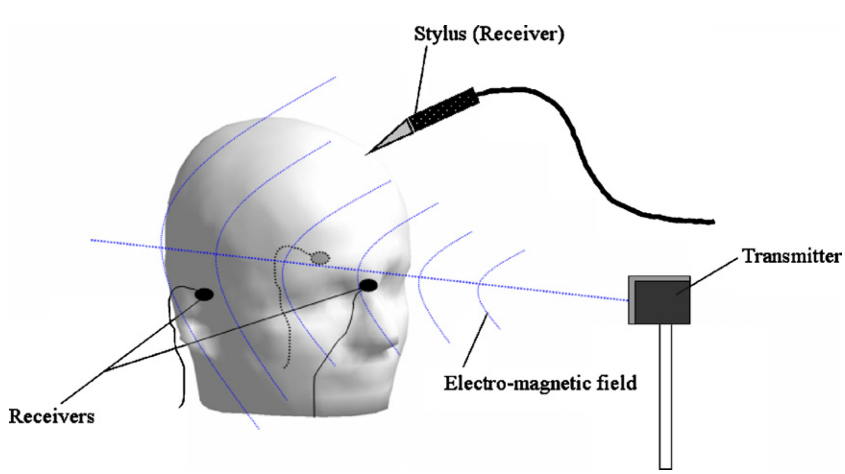

Figure 4 Electromagnetic digitization with the Fastrack system.

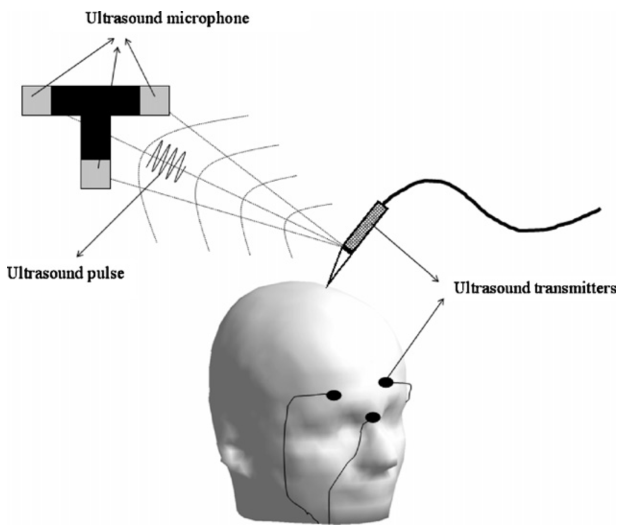

Figure 5 Principle of Elpos system (Zebris, Tuebingen, Germany).

The photogrammetry system (GPS)

This system was developed by Electrical Geodesics Inc (Eugene, United States). The method consists in positioning a subject wearing the Geodesic Sensor Net (GSN) in the center of a polyhedron-based photogrammetry structure, which has a camera mounted at each of its 11 vertices (Figure 6). After verification of the subject's position, a Net Station and all the 11 CCD cameras take a single picture simultaneously.

The GPS system requires a sensor to be visible in at least two cameras to determine its position. Once the operator marks the sensors in the acquired images, the GPS software determines sensor correct ID numbers (according to the built-in GSN sensor layout map), and uses triangulation to create a 3D model of the GSN (Figure 7, adapted from Russel et al., 2005).

The differences between the 2D user marks and the cloud of the estimated 3D points are indicative of the accuracy of the reconstructed sensor model.

The advantage of this method is that the patient is free to go when the pictures are taken. The acquisition time is very fast and comfortable for the subject. Its first disadvantage is, like digitization, to require cumbersome material. Secondly, the GPS must be used with the associated product, that is, the Geodesic Sensor Nets (Electrical Geodesics Inc, Eugene, United States). Thirdly, the detection is done manually (i.e., marking the sensors on the acquired images), which makes the system boring and time consuming for the operator.

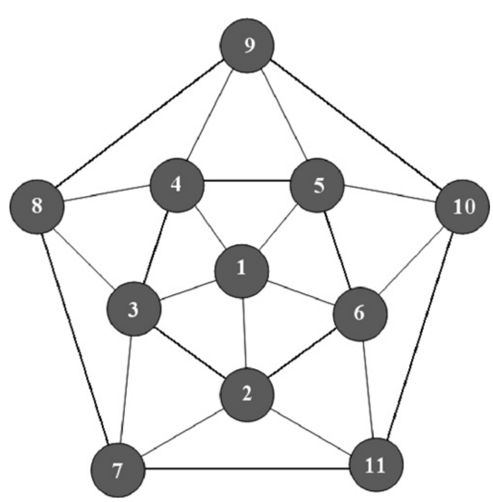

Figure 6 Photogrammetry system: Positions of the cameras on the dome.

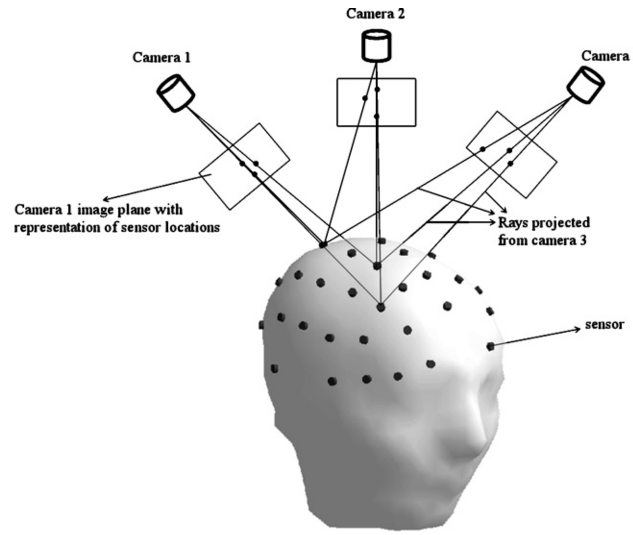

Figure 7 Photogrammetry system: Method for determination of 3D sensor position.

Spatial localization in MRI volume data

Few methods have been described in the literature regarding the localization of the EEG electrodes on MR images [1,6,8,12,16]. These methods use external paramagnetic markers, which are taped to the head:

- marker capsules constructed from rigid *lexan tubing*—the tube segments are filled with a $CuSO_4$ solution (2% *agar*, 2% *betadyne*, 1 g/L $CuSO_4$) [1];
- marker capsule filled with a 0.5 mmol/L solution of a *gadopentetate dimeglumine* based contrast agent (Magnevist, Berlex Laboratories Inc. Wayne, NJ, United States); the capsules measure 15 or 20 mm height and 12 mm in diameter (Figure 8, adapted from [16]);
- markers likes small *Vaseline*-filled capsules [8];
- markers like *Vitamin A* (Lambo, 8 mm) [12] or *Vitamin E* capsule [7].

The electrodes that are used in these studies are supposed MR-compatible, yet very few studies have presented MR compatibility tests. To localize the EEG sensors on the MR images, the MRI sequence is usually a high-resolution 3D anatomical T1 SPGR. The segmentation and the head modeling are not affected by the presence of the markers on the images. Several methods of detection and localization use morphological operations (closing, opening, expansion, erosion, smoothing etc). Moreover semi-automatic or automatic methods have been developed in order to speed up detection and labeling [6,12,15]. The spatial localization on MR images offers direct localization of the EEG electrodes in the fiducial system (nasion, left and right pre-auricular), thereby simplifying co-registration with the MRI volume (Figure 9).

The spatial localization of EEG electrodes in MRI volume presents several advantages for source localization. Indeed, one only needs adapted EEG sensors and MRI data in order to model the patient's head and to obtain the 3D coordinates of the sensors that are necessary for the co-registration. That is to say that no additional material is needed to localize the sensors, as compared to electromagnetic

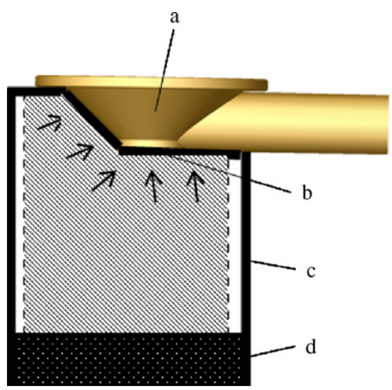

Figure 8 MRI measurement of electrode position: Marker used in Yoo et al.'s study. (a) Side view of an electrode. (b) A thin rubber diaphragm allows the capsule to fit over electrodes with tight contact (arrows). (c) Acrylic capsules are roughly cylindrical in shape (height 15 mm, diameter 12 mm) with a groove, which allows these to fit on top of the electrodes. (d) A black rubber cap (bottom of the capsules in this drawing) is used to allow the injection of doped water and extraction of air bubbles.

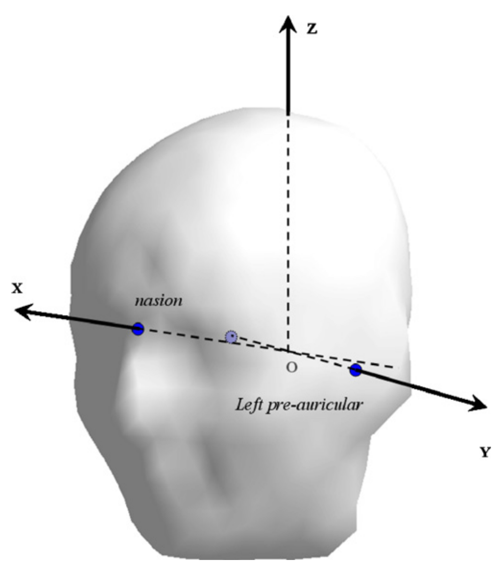

Figure 9 Fiducial system used for source localization.

digitization. The only required step is the detection and the spatial localization of the electrodes. However, this step is not binding if automatic algorithms are used. Noteworthy, no studies have been conducted with a high number of markers (maximum 33 electrodes). The only limitation of direct MRI co-registration is the MR compatibility of the electrodes and wires, and of course, access to an MRI machine.

Discussion

Comparison between the 10—20 coordinates, MRI localization, and electromagnetic digitization coordinates

Some studies did compare the accuracy of electromagnetic digitization and MRI localization. Generally, the 10—20 electrode coordinates are used as a gold standard to compare both methods.

The following results were obtained for a spherical head model with 30 electrodes taped on its surface:

- angular coordinates (θ and φ) located with MRI on 10 different subjects showed variations of about $17.7 \pm 4.8^\circ$ for θ (azimuth) and $18.8 \pm 5.5^\circ$ for φ (latitude) between standard 10—20 electrode coordinates [8];
- angular coordinates (θ and φ) located with the Fastrack system (Polhemus) on 10 different healthy subjects showed variations of about $4.1 \pm 3.6^\circ$ for θ (azimuth) and $4.5 \pm 3.7^\circ$ for φ (latitude) between standard 10—20 electrode coordinates [7].

These experiments are subject to errors because of the shape of the head. A better correlation can be measured with the frontal and temporal electrodes.

Comparison between manual measurements and electromagnetic digitization

Two studies did compare manual measurements and electromagnetic digitization [1,9]. The first one showed a mean intra-observer error of location of about 0.39 ± 0.01 mm between manual measurements with callipers and the Fastrack system, and a mean inter-observer error of about 0.43 ± 0.04 mm. This study was performed with 21 electrodes that were taped on a phantom head surface. The second study was performed with 64 electrodes in 11 healthy subjects. The mean intra-observer error was about 3.6 ± 0.5 mm. With regard to time consumption, digitization took 7.95 min whereas manual measurements (inter-electrode distances) took 5.66 min.

Comparison between MRI localization and 3D electromagnetic digitization

This study was performed by Brinkmann et al. [1] using 21 electrodes on a realistic head model. The authors first calculated digitizer measurement accuracy and showed that the inter-observer distance error was 0.39 ± 0.01 mm and the composite intra-observer distance error 0.43 ± 0.04 mm. Thereafter, the author demonstrated that the fiducial registration error (FRE) between corresponding marker centroids following registration, was 2.21 ± 0.97 mm with a maximum error of 4.87 mm. Finally, as a test of accuracy, the fiducial localization error (FLE) between the MRI and digitized inter-electrode distances was 0.90 ± 0.67 mm.

Comparison between electromagnetic digitizer and GPS

To compare the accuracy of the GPS method with the current standard for electrode digitization, Russel et al. [11] marked 37 points using a computer controlled laser-pointing method on a modified bowling ball (Columbia 300 White Dot) [11]. The cartesian coordinates of these points were chosen as a gold standard to compare digitization and GPS methods.

For the GPS, the RMS position error of sensor localization measurements was 1.27 mm (SD = 0.08). For the Polhemus Fastrack the RMS position error was 1.02 mm (SD = 0.04). This difference was not significant [$F(1,70) = 3.02$]. Thereafter, the GPS was tested on four patients with 129 sensors in order to estimate the performance of the semi-automatic localization. The mean results showed that 96 sensors were triangulated across two or more cameras, 11 sensors were triangulated only by one camera, and 22 sensors were not detected.

Conclusions

The spatial localization of EEG electrodes is an important step in the co-registration of EEG and MRI data. The method has to be accurate, fast, reproducible, and cheap [9]. Nowadays, the precise level of accuracy that is necessary or meaningful for surface electrode localization is still unclear. Noteworthy, the precision of spatial localization of EEG electrodes is only one parameter among others, such as the noise in the EEG data, which can influence source localization. To conclude, it seems that the error magnitude must be less than five millimeters for dense arrays of electrodes and source inversion algorithms [1]. Among the various methods that were just presented, the spatial localization of EEG electrodes with MRI is the most adapted to source localization because it does not require additional material and permits the use of MRI data in a double way: first, to perform MRI segmentation in order to construct the realistic head model and, second, to localize precisely the EEG sensors that are positioned on the patient's scalp. However, new EEG sensors must be developed to improve the method. These should fulfill the following requirements:

(1) to be MR compatible, that is, with no artifact susceptibility on the MR images;
(2) to be MR safe, that is, without induced currents that could harm the subject;
(3) to be MR localizable.

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