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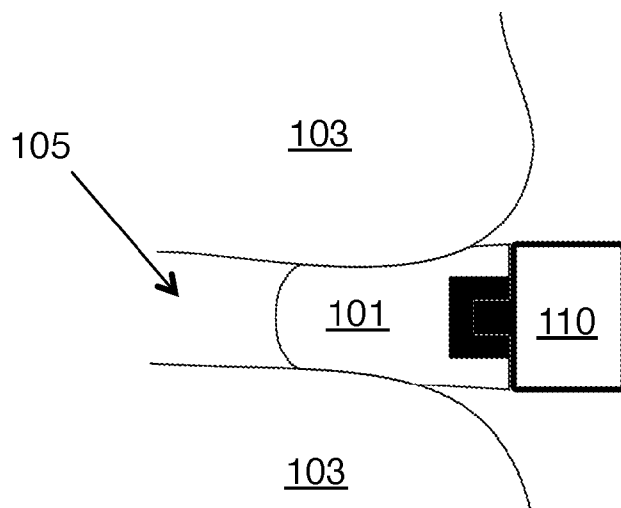


FIG. 1A

(57) Abstract: Hearing protection combined with head motion tracking for magnetic resonance (MR) procedures is provided. Trackable earplugs include an MR-visible sample combined with a passive resonant circuit. The trackable earplugs act as wireless markers for the MR system. A third wireless MR marker can be disposed on the forehead of the subject to facilitate motion tracking in six degrees of freedom (i.e., 3 rotations, 3 translations). Preferably, the coordinate system for motion tracking is rotated relative to standard MR coordinates to ensure distinct tracking peaks from the two trackable earplugs.





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Devices and methods for trackable hearing
protection in magnetic resonance imaging

FIELD OF THE INVENTION

5 The present invention relates to motion tracking and hearing protection in magnetic resonance imaging.

BACKGROUND

 Magnetic resonance imaging (MRI) is a valuable medical
10 imaging technique, both for research and for clinical purposes. MRI is often used for imaging the human brain, largely due to its excellent soft tissue contrast and ability to generate images with many different contrasts. Magnetic resonance imaging of the brain is typically
15 performed with the patient lying in a long narrow bore and with their head placed in a coil. The coil receives signal from tissue and, in some cases, transmits radiofrequency (RF) energy, in order to generate signal from the subject.

 One challenge in MRI is the acoustic noise that is
20 produced during a scan. The main source of this acoustic noise is the rapidly switching gradient fields in the strong static (B₀) field. At 3 T, the noise generated can exceed 125 dB. This can cause anxiety for the patient, temporary hearing loss, and potentially even permanent
25 hearing damage. For these reasons, hearing protection must be worn for every subject undergoing an MRI scan at common clinical field strengths (e.g. 1.5 T and 3 T) and at the higher field strengths (e.g. 7 T) used in research. The hearing protection typically used includes foam earplugs
30 and/or headphones. Earplugs generally provide a higher degree of noise attenuation than headphones; however, they

require practice to insert correctly. If not inserted properly, they can become loose over time and are no longer effective.

Another challenge in MRI is that the duration of each scan is on the order of minutes, and a complete examination can require around an hour. Most patients have difficulty remaining perfectly still for this length of time. This is problematic, because even motion of a few millimeters or less results in artifacts in the reconstructed images. In many cases, scans must be repeated, and in some cases, the patient must return to repeat the entire exam. Additionally, there are many patient populations (e.g. young children) who are simply unable to hold still and, as a result, these patients are often sedated. The problem of head motion in MRI therefore incurs a large financial cost, a potential risk to the patient for adverse events relating to the sedative, and inconvenience and stress for the patient and their family. Finally, there is a risk of misdiagnosis through poor quality images, for example, due to lesions obscured by motion artifacts.

In U.S. Patent App. US 2014/0171784 ('Method for 3D motion tracking using inductively coupled microcoils', hereby incorporated by reference in its entirety), Ooi et al. describe a method for tracking head motion in real time using small coils referred to as 'wireless markers'. Given real-time knowledge of head motion, it is possible to adaptively update the MRI scanner to compensate for the motion as it occurs. This general technique is known to those in the field as 'prospective' or 'adaptive' motion correction. Ooi et al. teach that in order to track head motion in the required six degrees of freedom (three translations, three rotations), three wireless markers are required. The three markers must all be attached to the

same rigid body and arranged non-collinearly (collinear markers cannot measure rotations around the line that intersects them all). For these reasons, Ooi et al. use a pair of glasses to hold three markers at pre-defined
5 locations. The glasses are worn by the subject during their MRI scan.

A key challenge of the approach described by Ooi et al. is that motion of the glasses is assumed to be equivalent to motion of the head of the subject. While this
10 is often true, there are many head coils that fit extremely closely to the head of the subject. In these situations, it is possible for the glasses to physically contact the head coil and then move relative to the head. This can lead to erroneous motion tracking estimates. In addition, the
15 requirement to wear glasses makes the subject's head larger and thus may not allow some patients to fit in the head coil.

From the above, it is clear that there is a need to both (a) obtain real-time head motion information in cases
20 with a highly enclosed head coil and (b) to monitor hearing protection systems to ensure that they are functioning as intended. Accordingly, it would be an advance in the art to address these issues.

25 SUMMARY

This work addresses both of these challenges conveniently at the same time. Rather than mounting wireless markers on a separate physical body (e.g., glasses), the human body itself becomes the scaffold on
30 which the wireless markers are attached to. These advancements both improve the practical applicability of the Ooi method and enable several other applications. In

particular, this work addresses the two needs discussed above: it allows real-time motion information to be obtained in a tightly constrained space and simultaneously monitors the subject's hearing protection to ensure it is still correctly positioned. While this work is particularly applicable for use in human subjects undergoing MRI, aspects of this work will have application to animal imaging in some cases.

In a preferred embodiment, wireless markers are integrated into earplugs worn by the subject. In this embodiment, each earplug includes two parts: a disposable part which can be a modified foam earplug, designed to closely fit into the ear canal and attenuate noise; and a reusable wireless marker part, which attaches to the foam earplug. We refer to the combined unit of both parts as a 'trackable earplug'. In this preferred embodiment, the foam part of the trackable earplug has a cylindrical hole, in which the wireless marker part can be inserted.

In a preferred embodiment, the wireless marker is completely encased in a cylinder of epoxy or plastic. It can therefore be sterilized using the alcohol solutions typically used for cleaning foam padding and other items that come into contact with a patient's skin during an MRI exam. In this preferred embodiment, the components of the active marker include an MR-visible sample, a coil wound around the MR-visible sample, a capacitor used for forming a resonant circuit, tuned to the resonance frequency of the sample, and a pair of crossed diodes to limit the voltage across the coil and hence the current flowing through it. In a preferred embodiment, the sample is spherical with a radius of 1 mm or less. The coil is preferably wound as close as possible to the sample, so that it both supports the sample and requires as little space as possible within

the wireless marker unit. Ideally, the coil is arranged so that when inserted into the foam earplug to form the trackable marker, it lies as far into the ear canal as possible. In this way it moves rigidly with the head motion of the subject.

In another embodiment, the earplug is made of a two-component moldable paste. When both components of the paste are combined, it hardens within a few minutes. During the hardening period, the moldable paste conforms snugly to the ear and allows one to insert a microcoil in each ear.

In a preferred embodiment, all wireless markers are aligned so that the axis that passes through the coil within the wireless marker lies perpendicular to the B0 direction of the MR scanner during normal operation. Thus the coil axis is defined as being perpendicular to a loop (or loops) of the coil, such that the loop(s) of the coil wind around the axis of the coil. Here, we refer to this as the 'coil orientation condition'. The coil orientation condition ensures that the maximum possible signal is obtained from the coil of the wireless markers. In this preferred embodiment, wireless markers can be manufactured with a small protruding 'stem' to indicate the preferred orientation. Preferably this coil orientation condition is satisfied to within +/- 45 degrees. More preferably the coil orientation condition is satisfied to within +/- 10 degrees.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGs. 1A-B shows an earplug suitable for insertion in the ear canal of a subject, with an integrated connection mechanism allowing a wireless marker to be securely attached to it.

FIG. 1C shows a more detailed view of the wireless marker in **FIGs. 1A-B**.

FIG. 1D shows a wireless marker including two MR-visible samples.

5 **FIG. 1E** shows a wireless marker including a rod-shaped MR-visible sample.

FIG. 2A-B show a more compact version of the device in **FIG. 1A**, where the wireless marker is encased in epoxy and inserted into the earplug.

10 **FIGs. 2C-D** show a modification to the trackable earplugs shown in **FIGs. 2A-B**, where a tube allows delivery of acoustic stimuli for functional MRI through the earplugs.

15 **FIG. 2E** shows a more detailed view of the wireless marker design of **FIGs. 2A-D**.

FIG. 3A shows how two trackable earplugs, and an extra wireless marker worn on the forehead, can be attached to the subject during a magnetic resonance imaging exam.

20 **FIG. 3B** shows how the system in **FIG. 3A** can be used with a pneumatic tube to deliver audio to the subject.

FIG. 4 shows how regular headphones can be worn by the subject in addition to the three wireless markers.

25 **FIG. 5** shows how a mixture of gradient axes is used to obtain projections from the wireless markers where the projection peaks are non-overlapping.

FIGs. 6A-D show in more detail how peaks can overlap if the regular x, y and z gradients are used to provide the projections and how this can be avoided by using a mixture of gradients.

FIG. 7 shows how the distance between the two earplugs may be defined.

FIG. 8 is a flowchart describing an algorithm that can be used to stop a scan if an earplug is missing or comes
5 loose.

DETAILED DESCRIPTION

FIGs. 1A-B show an earplug **101** suitable for insertion in the ear canal **105** of a subject **103**. The earplug includes
10 a plastic insert **102** with a centered hole, which acts as a connecting mechanism. This allows a wireless marker **110** to be securely attached to it by inserting the matching connecting mechanism **111** on the wireless marker unit into the earplug. The combined 'trackable earplug', including an
15 earplug and wireless marker, can be assembled either before or after insertion of the foam portion into the ear canal. The earplug material preferably provides acoustic noise attenuation of at least 30 dB. The wireless marker allows the position of the trackable earplug to be obtained in
20 three degrees of freedom within the imaging volume of the MRI scanner, when used according to the methods described here.

FIG. 1C provides a more detailed view of the internal components of the wireless marker shown in **FIG. 1A**. The
25 plastic shell of the wireless marker **110** includes a connector **111** enabling it to be easily attached to the earplug. The earplug itself is preferably disposable, and this connecting mechanism allows the wireless marker to be removed from the earplug using the connector and reused.
30 The wireless marker **110** contains a MR-visible sample **120**, which can be spherical as shown. The MR-visible sample **120** is surrounded by a coil **121**, which serves to receive signal from the sample. Although coil **121** is shown here as having

multiple loops, it is also possible for coil **121** to have a single loop. A resonant circuit is constructed from the coil **121** and a capacitor **122**, and the resonant circuit is tuned to the known resonance frequency of the sample. Two
5 crossed diodes **123** connected in parallel are also included to limit the voltage across the coil, particularly during RF transmit for protection. Our experiments indicate that the crossed diodes are useful to prevent heating during imaging with RF-intensive sequences. Importantly, the coil
10 **121** is arranged so that when inserted into the ear canal of a subject lying in an MRI scanner, the axis **124** of the coil is perpendicular to the direction of the scanner B0 field. Here we refer to this as the 'coil orientation condition'. This means that the axis that passes through the coil is
15 parallel to the long axis of the earplug. This ensures when the earplugs are inserted into the ear canal, the coil orientation condition holds.

Although the ear canal does not lie perfectly perpendicular to the B0 field direction (i.e., the head to
20 foot direction) for most subjects, the approximation is sufficient to adequately fulfill the coil orientation condition. Slightly tilting the coil axis orientation relative to the longitudinal axis of the earplug to counteract the angle of the ear canal is counterproductive:
25 the earplug is best made rotationally symmetric, such that the subject and scanner operator cannot inadvertently rotate it to an incorrect orientation and potentially violate the coil orientation condition. The coil orientation condition is particularly important for the
30 third wireless marker, since there is no 'ear canal axis' to guide placement. Instead, when the third wireless marker is placed on the forehead, the coil axis preferably points in the subject's left-right direction or the subject's

anterior-posterior direction. In either case, the coil axis ends up being perpendicular to the B0 magnetic field of the MR system, as desired.

In a preferred embodiment, the MR-visible sample 120
5 contains water doped using standard MRI contrast agents to reduce the relaxation times T1 and T2 to values below that normally found in human soft tissue. The reason for doping the sample is to prevent the active marker component of the trackable earplugs from being visible in the MR images
10 during imaging. Our research has shown that if the sample is not sufficiently doped, then signal from previous excitation can remain in the sample and propagate into nearby MRI imaging slices. This can be avoided if the relaxation times T1 and T2 are sufficiently short, because
15 then signal does not remain for long enough to be detectable in any MRI sequence apart from the MRI navigator tracking sequence that is specifically designed to track the wireless markers. In another embodiment, the tracking sequence used is a variant of ultrashort echo time (UTE)
20 imaging. In this embodiment, the markers are doped such that their T2 relaxation time is less than 1 ms.

In another embodiment, the wireless markers also include a resistor, or resistive wire. This reduces the Q factor of the resonant circuit, which also reduces the
25 likelihood of the markers being visible in a regular imaging sequence. A lower Q factor also reduces sensitivity to small mismatches between the resonant frequency of the circuit and the proton resonant frequency.

One embodiment of the invention is a device for
30 tracking the head of a living subject in a magnetic resonance (MR) system. Here MR system includes both MR imaging systems and MR spectroscopy systems where MR data other than imaging data is collected. The device includes

two earplugs, where each earplug includes an integrated MR-visible wireless marker. Each wireless marker includes: a) an MR-visible sample having a sample resonant frequency, and b) a coil disposed around the MR-visible sample. Here
5 the coil has a coil resonant frequency that is tuned to the sample resonant frequency, and as indicated above it is convenient to define the axis of the coil as being perpendicular to loop(s) of the coil.

Two or more wireless markers can be included in the trackable earplug. **FIG. 1D** shows a preferred configuration for this. In this example, each trackable earplug contains two wireless markers **110** and **130** integrated with each other such that the axis connecting each pair of wireless markers is perpendicular to the axis **124** connecting the left and
15 right trackable earplugs. This configuration allows complementary projection data and allows determination of rotational motion of the head around the axis connecting the left and right trackable earplugs (i.e., axis **124**). In this embodiment, the wireless marker on the forehead is not
20 needed to get six-degree-of-freedom head motion information.

In another embodiment, each wireless marker contains a sample that is not spherical, but has some other shape. **FIG. 1E** shows an example where the MR-visible sample **130** is
25 rod-shaped. In this case, it is possible to obtain rotation information by analyzing the shape of each projection. This means that it is possible to obtain six-degree-of-freedom head motion information with fewer than three markers.

30 In another embodiment, each wireless marker is not identical, but rather differs from the others in a unique way. One such embodiment is when MR visible beads, or spherical samples, of different sizes are used. That way,

the peak width differs for each wireless marker, allowing them to be uniquely identified. Another such embodiment is when multiple MR visible beads, or spherical samples, are included within each wireless marker. In this case,

5 multiple peaks appear in close proximity, forming a 'peak cluster'. The number of peaks in each 'peak cluster' can be used to uniquely identify each wireless marker.

In another embodiment, foam earplugs are equipped with small optically visible samples, such as reflective
10 spheres. The position of each reflective sphere can be monitored using a camera to obtain motion information from the subject. If the reflective spheres are used in conjunction with wireless markers, then the relative location of the two marker types can be found using a
15 cross-calibration procedure.

FIGs. 2A-B show a more compact design of the trackable earplug shown in **FIGs. 1A-B**. In this design, the earplug **201** contains a cylindrical hole **202** designed to fit over a miniaturized wireless marker **210** in the form of a
20 cylindrical plug. **FIGs. 2C-D** show that the trackable earplugs of **FIGs. 2A-B** can be manufactured to contain a small tube **203** with internal diameter of ~1 mm, so that acoustic stimuli can be delivered to the subject through the trackable earplugs. The approach of **FIGs. 2C-D** is an
25 alternative to wearing pneumatic headphones and is particularly useful for fMRI (functional MRI) applications within enclosed head coils. Acoustic fMRI stimuli can then be delivered to the subject through the trackable earplugs, without the need for large external headphones.

30 **FIG. 2E** shows how the components of the wireless marker can be arranged so that they can be formed into a cylindrical plug made of epoxy. The coil **223** is preferably arranged so that it serves as a sample holder for the MR-

visible sample **224**. Although coil **223** is shown here as having multiple loops, it is also possible for coil **223** to have a single loop. The tuning capacitor **222** and crossed diodes **221** are placed further along the cylindrical plug, so as to minimize the diameter of the plug. As in the design shown in FIG. **1C**, the coil **223** is arranged so that when inserted into the ear canal of a subject lying in an MRI scanner, the axis **225** of the coil is perpendicular to the direction of the scanner B0 field.

FIG. 3A shows how two trackable earplugs **320**, and a third wireless marker **321**, can be attached to the subject **310** during a magnetic resonance imaging exam. Here the subject wears another wireless marker **321**, which can be placed on their forehead anywhere between the bridge of their nose and their hairline (or somewhere else on the head that allows sufficient separation of signals from the remaining two microcoils). This third wireless marker is not integrated into a trackable earplug; however, it is otherwise identical to the wireless markers used within the trackable earplugs.

The third wireless marker **321** enables tracking of the subject's head motion in six degrees of freedom, when the methods described here are applied. The third wireless marker **321** (which can be potted) is attached to the forehead. It is not attached to the hair of the subject **311**, since hair typically moves relative to the subject's head in an unpredictable fashion. When the subject **310** is placed on the patient table **301** in an MRI scanner **300**, the orientation of the axes of the coils in the wireless markers all lie perpendicular to the direction of the B0 field. **FIG. 3B** shows how the setup in **FIG. 3A** can be used to deliver acoustic stimuli (or other audio signals) **323** to the subject using a tube **322**. In the example in **FIG. 3B**,

the earplugs used are those shown in **FIGs. 2C-D**, i.e., they contain a small tube that penetrates the earplug.

FIG. 4 shows how the setup in **FIGs. 3A-B** is compatible with standard MRI-compatible headphones **402**. In this case, the subject **310** lies on the patient table **301** inside the MRI scanner **300** and wears two trackable earplugs **320**. If motion tracking in six degrees of freedom is required, then an extra wireless marker **321** is attached to the skin on the forehead below the subject's hair **311**. The subject **310** wears headphones **402** over the top of the trackable earplugs **320**. The earplugs are sufficiently deep in the ear canals of the subject that there is no physical contact between the headphones and the trackable earplugs. Likewise, there is no physical contact between the headphones and the extra wireless marker attached to the forehead. It is important that the headphones do not contact either marker type, since the headphones may move with respect to the head and if such motion is transferred to the markers, head-tracking quality is affected. Thus the headphones do not interfere with the operation of the trackable earplugs or third wireless marker attached to the forehead. The use of headphones as shown in **FIG. 4**, reduces the minimum allowable acoustic attenuation requirement of the trackable earplugs. In addition, headphones provide the ability to listen to audio, including instructions from the scanner operator.

An exemplary embodiment is a method for tracking the head of a living subject in a magnetic resonance (MR) system. Here also, MR system includes both MR imaging systems and MR spectroscopy systems where MR data other than imaging data is collected. The method includes

a) providing two trackable earplugs where each earplug includes an integrated MR-visible earplug wireless marker.

Each earplug wireless marker includes an MR-visible sample having a sample resonant frequency, and a coil disposed around the MR-visible sample. Here the coil has a coil resonant frequency that is tuned to the sample resonant
5 frequency. The axis of the coil is defined to be perpendicular to loop(s) of the coil.

b) disposing the earplugs in ear canals of the subject; and

c) tracking positions of the earplug wireless markers
10 by obtaining projections from one or more localization gradients in an MR pulse sequence.

Variations of this basic method mainly relate to a) further aspects of motion correction, b) the coordinates used for tracking, and c) marker distance monitoring.
15 These topics are considered in turn below.

As described above, use of a third wireless marker (e.g., disposed on the forehead of the subject) combined with position tracking of the earplug wireless markers and the third wireless marker provides head motion tracking for
20 three orthogonal translations and three orthogonal rotations (i.e., six degrees of freedom).

Performing motion correction based on the tracking positions of the earplug wireless markers and of the third wireless marker can be done. This motion correction can be
25 applied retrospectively, but in this preferred embodiment motion correction is applied adaptively. Such motion correction can be applied adaptively to MR imaging by updating encoding magnetic fields of the MR system in real time. The adaptive motion correction procedure is
30 described in Ooi et al. and its application to imaging is known well to those skilled in the art. Such motion correction can also be applied adaptively to a navigator

sequence for MR tracking, whereby improved tracking can be provided (e.g., preventing overlap of the peaks in the projections of the wireless markers, even under extreme rotation).

5 In another embodiment, the trackable earplugs are used during a PET-MR (positron emission tomography - MR) examination. The motion tracking data is then used to correct the PET data after acquisition. Similarly, motion tracking using MR-visible earplugs can be used to provide
10 motion correction for any non-MRI medical imaging modality in cases where the non-MR medical imaging modality is performed in combination with MR motion tracking (and optionally MR imaging). Here the motion correction is applied to the data obtained from the non-MR medical
15 imaging modality.

FIG. 5 shows a two-dimensional example illustrating how a combination of gradient axes is used to obtain projections from the wireless markers, such that the projection peaks do not overlap. In this example, the
20 method taught by Ooi et al. in US 2014/0171784 is insufficient because a projection on the physical z-axis only shows two peaks. This coincidence of the peaks is because both trackable earplugs have the same z coordinate. By using a combination of gradients to obtain projections,
25 peaks can be sufficiently separated from each other, e.g., as in projections **502** and **504** on **FIG. 5**.

For clarity, the same concept is illustrated in three dimensions in **FIGs. 6A-D**. If projections **604**, **606**, **608** and **610** are acquired using an x-y-z coordinate system (where x, y and z correspond to the physical gradient axes x, y and z, respectively) they would be insufficient to obtain
30 unique peaks from markers m_1 , m_2 , m_3 , due to the geometry of the head **602** in the MRI scanner and the arrangement of the

markers. Instead, a u - v - w coordinate system is used for marker tracking, which is a rotated version of the x - y - z coordinate system. Here it is apparent that projections **612**, **614**, **616** and **618** in the u - v - w coordinates provide
5 separate peaks for markers m_1 , m_2 , m_3 in three dimensions.

The rotation matrix required to give the location of a point in scanner physical x - y - z coordinates from its location in u - v - w coordinates is referred to as **R**. The rotation matrix **R** is known and preferably predefined before
10 the beginning of the MRI examination. In fact, since the geometry of the head of each human subject is similar, in our preferred implementation, **R** is preferably constant for all subjects.

In the example of **FIGs. 6A-D**, the x - y - z standard MR
15 coordinates shown are for a subject lying on his or her back. For a subject lying on his or her side, the x and y directions of the standard MR coordinates are exchanged relative to what is shown. This does not significantly affect the above-described coordinate rotations to obtain
20 distinct peaks from the trackable earplugs. In either case, gradient coordinates of the localization gradients are rotated with respect to standard coordinates of the MR system such that peaks from the wireless markers are non-overlapping for three or more projections.

25 In a preferred embodiment, three projections are applied using the MRI scanner to detect the locations of each wireless marker. Importantly, these projections are preferably applied using a mixture of the physical scanner gradients. This is done, because as described above, three
30 projections applied using the x , y and z gradients individually are not sufficient to uniquely identify the locations of the three markers when arranged as described. In this embodiment, the mixture of gradients is selected so

that the new coordinate axes form an orthogonal coordinate system (where the coordinate surfaces all meet at right angles) and the three wireless markers form distinctly separate peaks when projected onto each of these three axes.

In a preferred embodiment, the locations of the peaks corresponding to each marker are identified, giving the location of each marker in u, v, w coordinates. The location of each marker is then determined in $x-y-z$ coordinates by multiplication with matrix $\mathbf{R}$. Using methods well known to workers in this field, the set of three points corresponding to the wireless marker locations in scanner $x-y-z$ coordinates can then be used to give motion information in six degrees of freedom. In another equivalent embodiment, this motion information is directly calculated in u, v, w coordinates and then converted to physical scanner coordinates using rotation matrix $\mathbf{R}$.

In another embodiment, the axes u, v, w form a skew (i.e., non-orthogonal) coordinate system, rather than an orthogonal coordinate system. This can help to ensure optimal peak spacing in the marker projections.

In another embodiment, more than three projections are applied to localize the markers. In this embodiment, any projections that contain fewer than the expected number of peaks are discarded. The marker location can then be found using a number of techniques known to those in the field, such as backprojection methods or by solving a linear system of equations, where the unknowns are the marker coordinates.

FIG. 7 shows how the Euclidean distance d_{12} can be defined between two wireless markers, labeled here as m_1 and m_2 . More specifically, if marker m_1 has coordinates $(x_1(t),$

$y_1(t)$, $z_1(t)$) and marker m_2 has coordinates $(x_2(t)$, $y_2(t)$, $z_2(t)$), then the Euclidean distance is given by

$$d_{12}(t) = \sqrt{(x_1(t) - x_2(t))^2 + (y_1(t) - y_2(t))^2 + (z_1(t) - z_2(t))^2}.$$

Here all coordinates are shown with a time dependence to
 5 account for possible motion of the earplugs after
 insertion. In this example, the Euclidean distance between
 two trackable earplugs worn by the subject in ears **702** and
704 is calculated. Monitoring this distance provides a
 great deal of useful information, specifically whether or
 10 not the subject is, in fact, wearing earplugs and whether
 the earplugs have moved at all since the first time this
 measurement was made.

In a preferred embodiment, the relative displacement
 between the two trackable earplugs is monitored during the
 15 MRI exam. If the displacement changes by more than a
 certain threshold (for example, by more than 1 mm along any
 axis), this indicates that one, or both, of the trackable
 earplugs has moved relative to the subject's ear canal.
 This indicates that the earplug may no longer be providing
 20 acceptable acoustic noise attenuation, because even a small
 air gap between the foam of the earplug and the internal
 surface of the ear canal severely compromises attenuation.
 The relative positional change information can be also used
 to monitor the third microcoil. In this preferred
 25 embodiment, the scan can be automatically stopped if such a
 situation arises. Similarly, in this preferred embodiment,
 if an earplug is not detected, the scan can be immediately
 and automatically stopped.

An exemplary algorithm for distance monitoring is
 30 summarized by the flowchart shown in **FIG. 8**. After starting
 the scan, the navigator sequence is played out on the

scanner. Since, in this example, the subject is wearing two trackable earplugs, it is expected that two wireless markers will be located by the navigator. If this is not the case, it is likely that one of the earplugs is missing (i.e. it may have fallen out prior to starting the scan, or the technologist or subject may have forgotten to insert it). In this case, the scan is stopped, so that the situation can be corrected. If, on the other hand, two markers are detected, then the Euclidean distance at the time of starting the scan, denoted $d(0)$, is calculated. The scan continues and the trackable earplug locations are periodically re-measured and the distance, $d(t)$, is calculated. If at any time the absolute difference between the latest distance, $d(t)$, and the initially measured distance $d(0)$, exceeds a threshold, then the scan is stopped, because this indicates that one of the trackable earplugs has become loose or fallen out completely. In this manner, it can be ensured that the subject is always wearing suitable hearing protection.

20

CLAIMS

1. A device for tracking the head of a living subject in a magnetic resonance (MR) system, wherein the device

5 comprises:

two earplugs, wherein each earplug comprises an integrated MR-visible wireless marker;

wherein each wireless marker comprises

an MR-visible sample having a sample resonant
10 frequency, and

a coil disposed around the MR-visible sample;

wherein the coil has a coil resonant frequency that is tuned to the sample resonant frequency;

wherein an axis of the coil is perpendicular to a
15 loop of the coil.

2. The device of claim 1, wherein the axis of the coil is configured to be perpendicular to a static B0 magnetic field of the MR system to within +/- 45 degrees when the
20 earplugs are worn during operation of the MR system.

3. The device of claim 1, wherein the axis of the coil is configured to be perpendicular to a static B0 magnetic field of the MR system to within +/- 10 degrees when the
25 earplugs are worn during operation of the MR system.

4. The device of claim 1, wherein the coil in the wireless marker is configured as a spherical holder to support the MR-visible sample.

5. The device of claim 1, wherein each earplug comprises a disposable part and a reusable part, wherein the reusable part comprises the MR-visible wireless marker, and wherein
5 the disposable part is configured for insertion into an ear canal of the subject.

6. The device of claim 5, wherein each earplug comprises a connecting mechanism configured to permit the disposable
10 part and the reusable part to be connected before or after the disposable part is inserted into an ear canal of the subject.

7. The device of claim 1, wherein the earplugs are
15 configured to be worn under a pair of headphones, whereby a user of the device may listen to audio during an MR procedure.

8. The device of claim 1, wherein the earplugs further
20 comprise a acoustic port, whereby acoustic stimuli or other audio can be delivered to the subject during an MR procedure

9. The device of claim 1, wherein the MR-visible samples
25 are non-spherical, whereby images of the MR-visible samples provide information on orientation of the wireless markers.

10. The device of claim 1,
wherein each earplug includes one or more integrated
30 MR-visible additional wireless markers;

wherein each additional wireless marker comprises
an MR-visible sample having a sample resonant
frequency, and

a coil disposed around the MR-visible sample;

5 wherein the coil has a coil resonant frequency that is
tuned to the sample resonant frequency.

11. A method for tracking the head of a living subject in a
magnetic resonance (MR) system, wherein the method
10 comprises:

a) providing two earplugs, wherein each earplug
comprises an integrated MR-visible earplug wireless marker;

wherein each earplug wireless marker comprises
an MR-visible sample having a sample resonant
15 frequency, and

a coil disposed around the MR-visible sample;

wherein the coil has a coil resonant frequency that is
tuned to the sample resonant frequency,

wherein an axis of the coil is perpendicular to a loop
20 of the coil;

b) disposing the earplugs in ear canals of the
subject;

c) tracking positions of the earplug wireless markers
by obtaining projections from one or more localization
25 gradients in an MR pulse sequence.

12. The method of claim 11, wherein gradient coordinates of
the localization gradients are rotated with respect to
standard coordinates of the MR system such that peaks from

the wireless markers are non-overlapping for three or more projections.

13. The method of claim 11, wherein the axis of the coil is
5 perpendicular to a static B0 magnetic field of the MR
system to within +/- 45 degrees when the earplugs are worn
during operation of the MR system.

14. The method of claim 11, wherein the axis of the coil is
10 perpendicular to a static B0 magnetic field of the MR
system to within +/- 10 degrees when the earplugs are worn
during operation of the MR system.

15. The method of claim 11, further comprising:

15 d) disposing a third wireless marker on the head of
the subject;

wherein the third wireless marker comprises

an MR-visible sample having a sample resonant
frequency, and

20 a coil disposed around the MR-visible sample;

wherein the coil has a coil resonant frequency that is
tuned to the sample resonant frequency.

e) tracking a position of the third wireless marker by
obtaining projections from one or more localization
25 gradients in an MR pulse sequence.

16. The method of claim 15, wherein position tracking of
the earplug wireless markers and the third wireless marker

provides head motion tracking for three orthogonal translations and three orthogonal rotations.

17. The method of claim 15, further comprising performing
5 motion correction based on the tracking positions of the earplug wireless markers and of the third wireless marker.

18. The method of claim 17, wherein the motion correction
is applied adaptively to MR imaging by updating encoding
10 magnetic fields of the MR system in real time.

19. The method of claim 17, wherein the motion correction
is applied adaptively to a navigator sequence for MR
tracking, whereby improved tracking can be provided.

15

20. The method of claim 17, further comprising obtaining
data from a non-MR medical imaging modality, wherein the
motion correction is applied to the data obtained from the
non-MR medical imaging modality.

20

21. The method of claim 11, further comprising monitoring a
distance between the earplug wireless markers as determined
from the tracking positions of the earplug wireless
markers, whereby changes in earplug wireless marker
25 position relative to the head of the subject during an MR
procedure can be detected.

22. The method of claim 21, further comprising determining
whether or not the earplugs have moved from their initial

positions during an MR procedure from the monitoring a distance between the earplug wireless markers.

23. The method of claim 11, further comprising determining
5 whether or not the earplugs have fallen out of the ear
canals of the head of the subject from the tracking
positions of the earplug wireless markers.

24. The method of claim 23, further comprising aborting an
10 MR procedure if it is determined that either or both of the
earplugs have fallen out.

25. The method of claim 11, wherein the MR-visible samples
are non-spherical, whereby images of the MR-visible samples
15 provide information on orientation of the wireless markers.

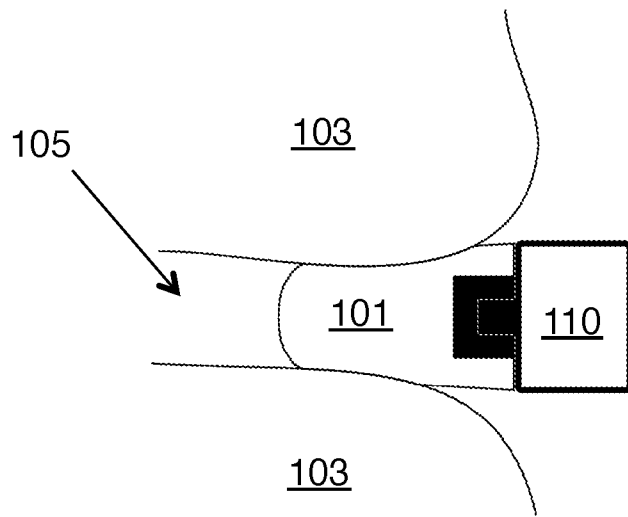


FIG. 1A

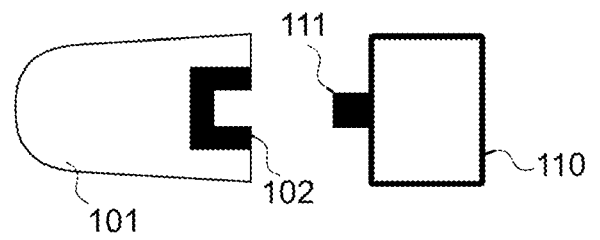


FIG. 1B

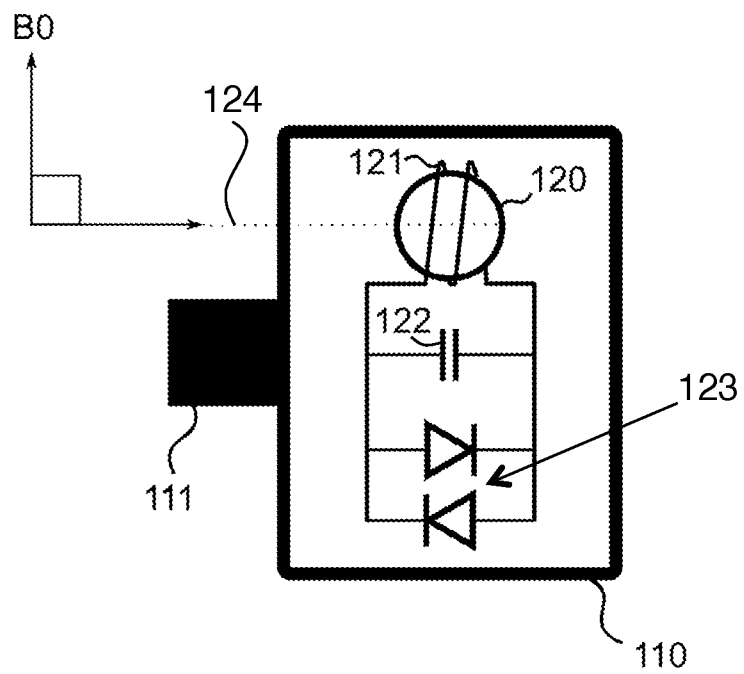


FIG. 1C

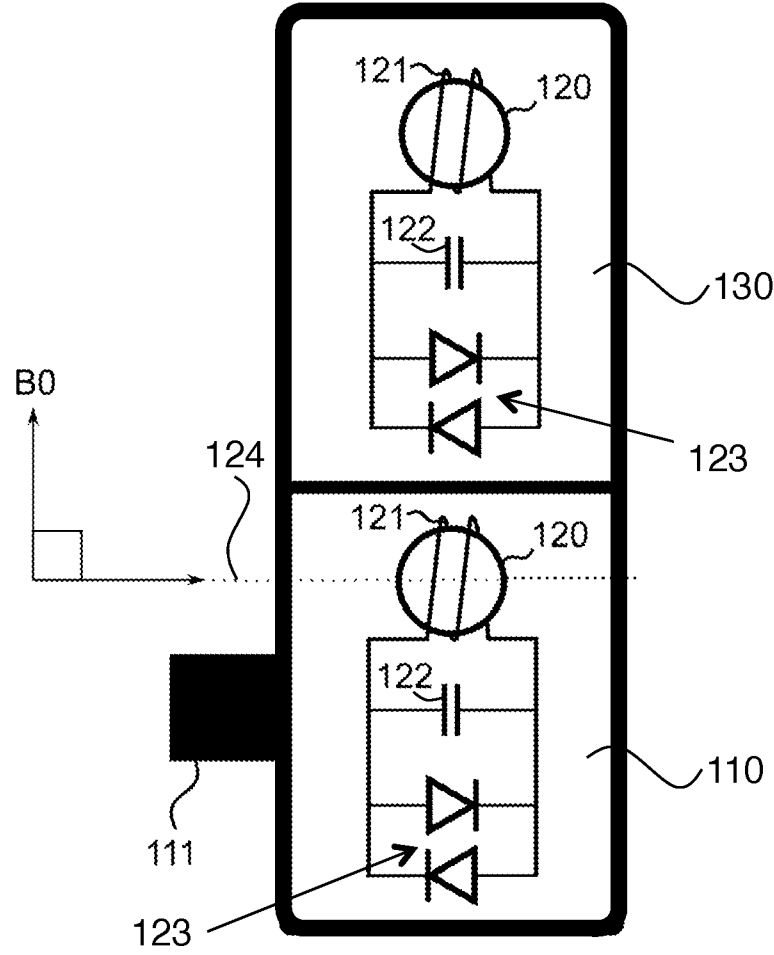


FIG. 1D

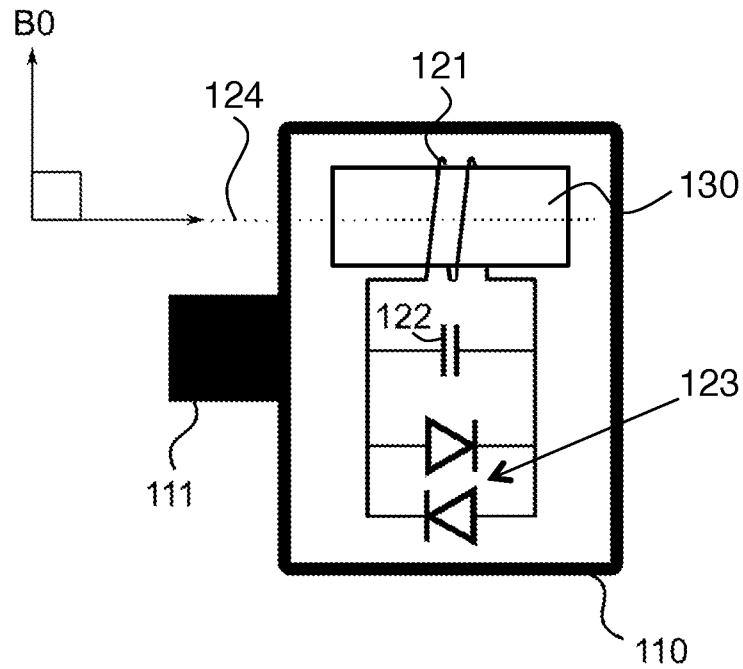


FIG. 1E

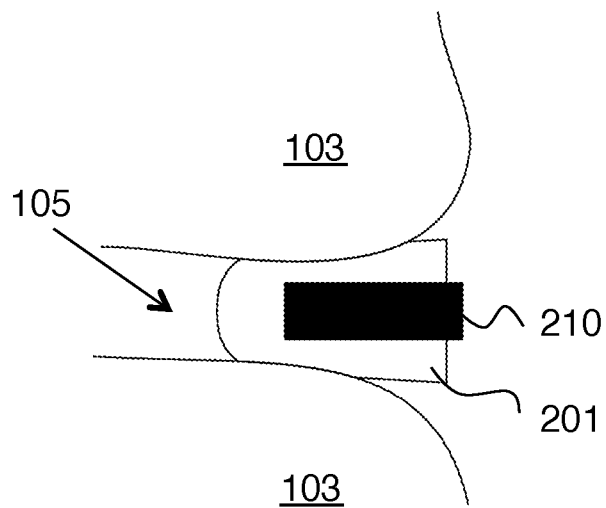


FIG. 2A

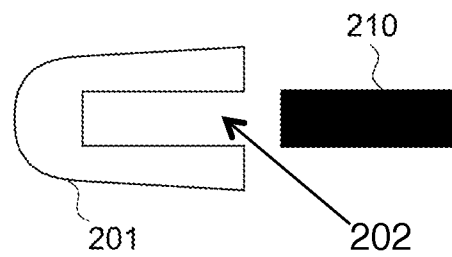


FIG. 2B

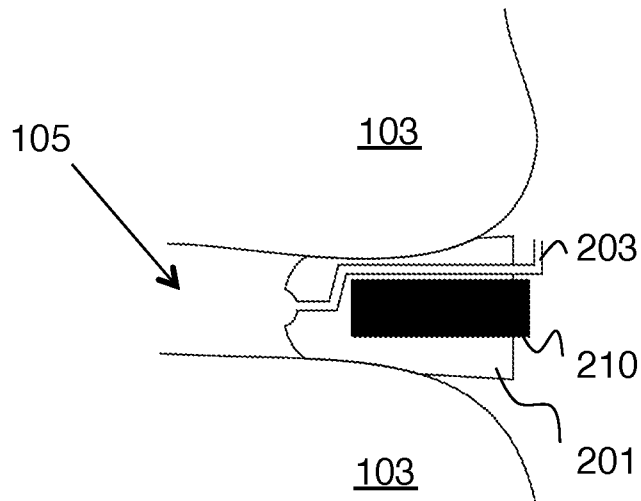


FIG. 2C

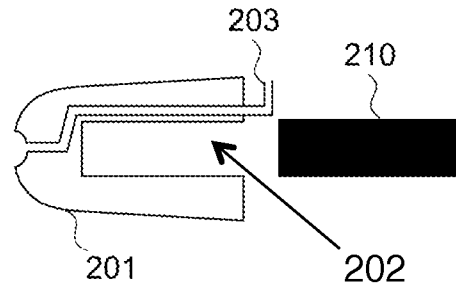


FIG. 2D

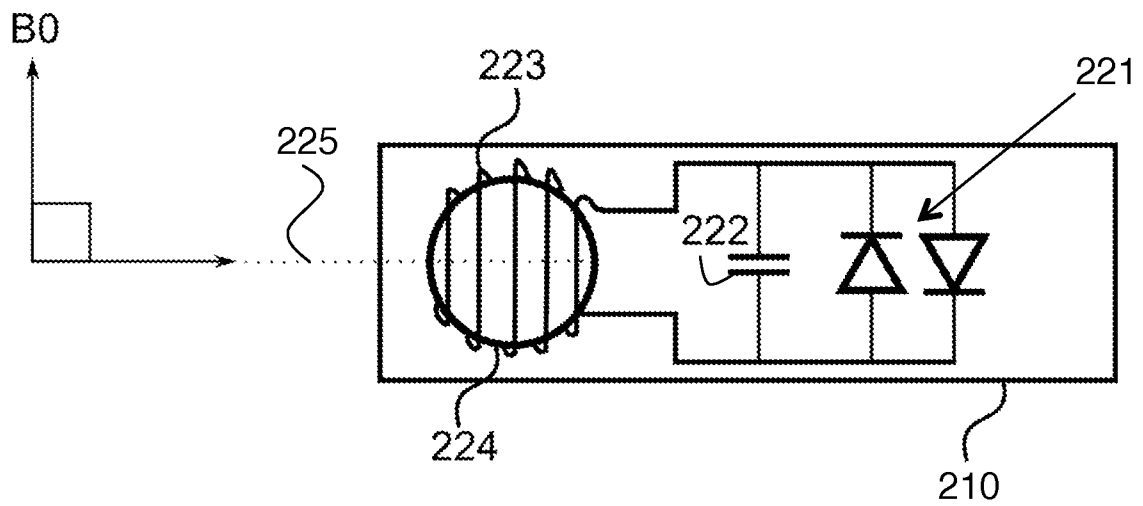


FIG. 2E

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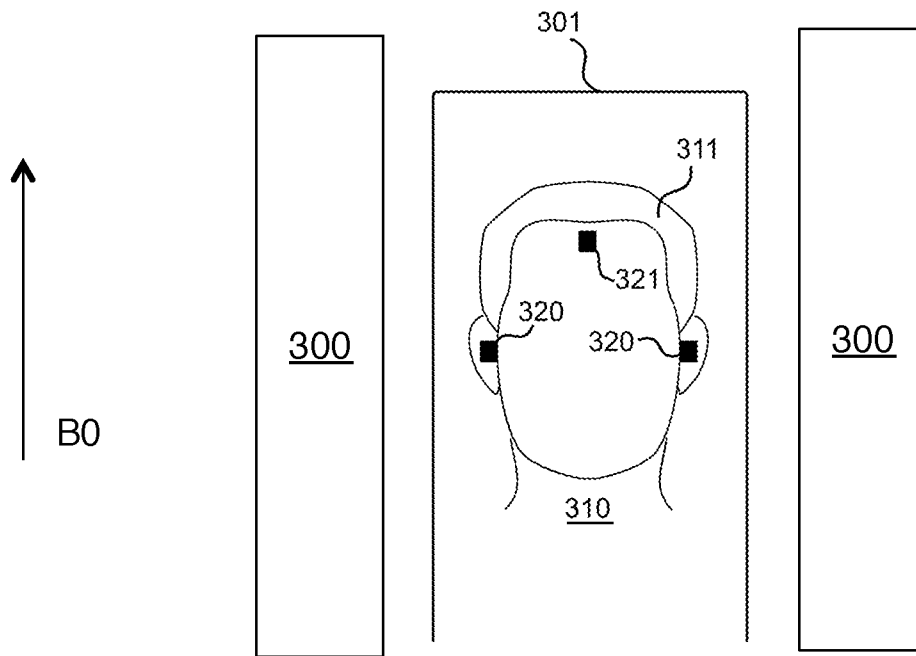


FIG. 3A

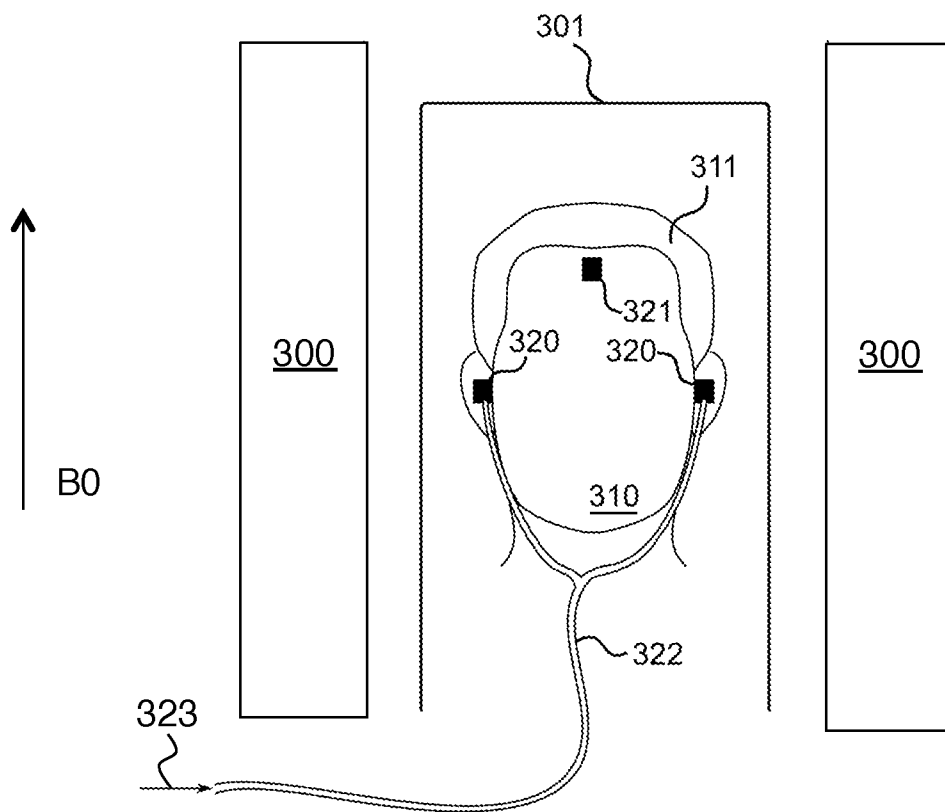


FIG. 3B

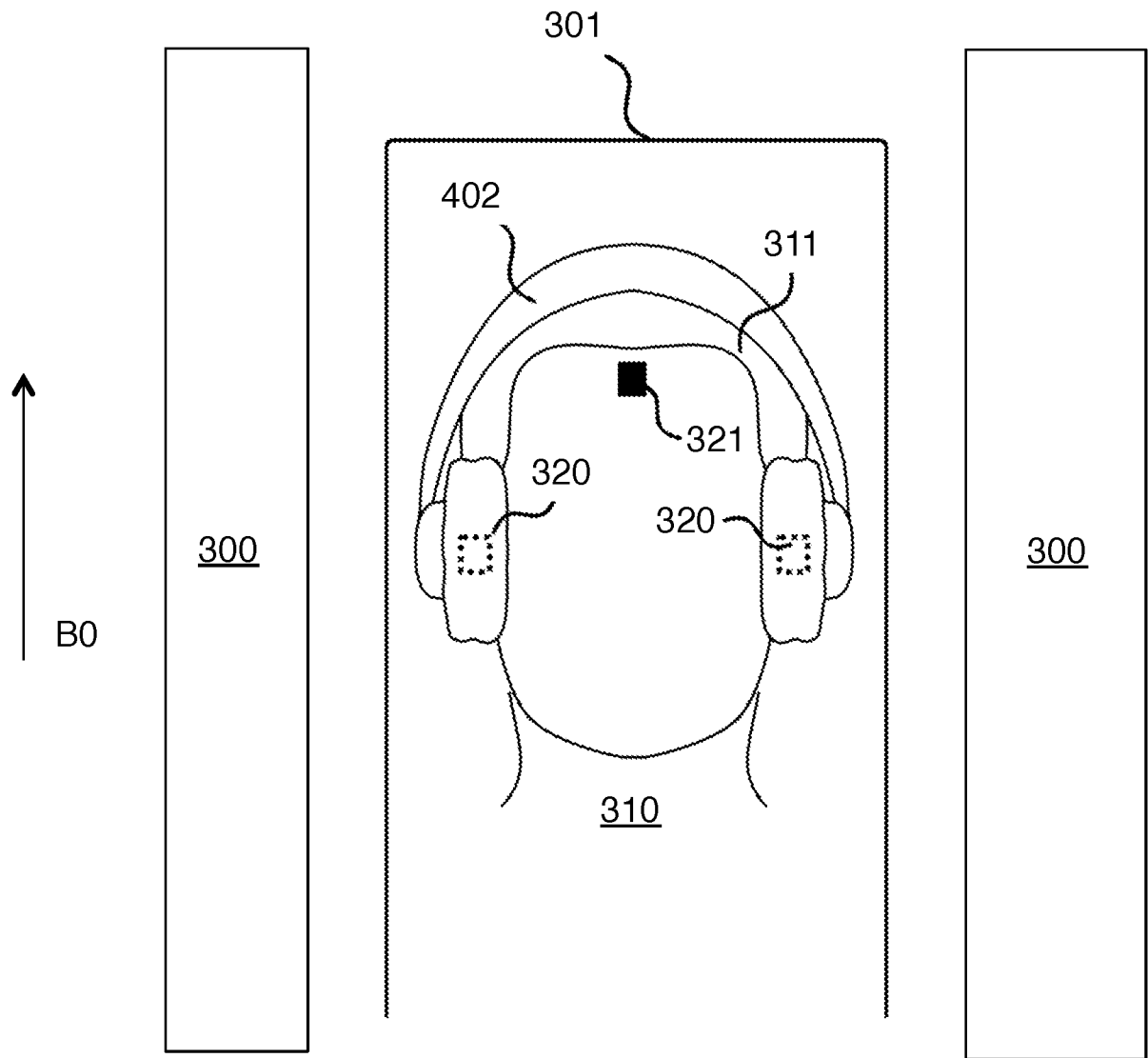


FIG. 4

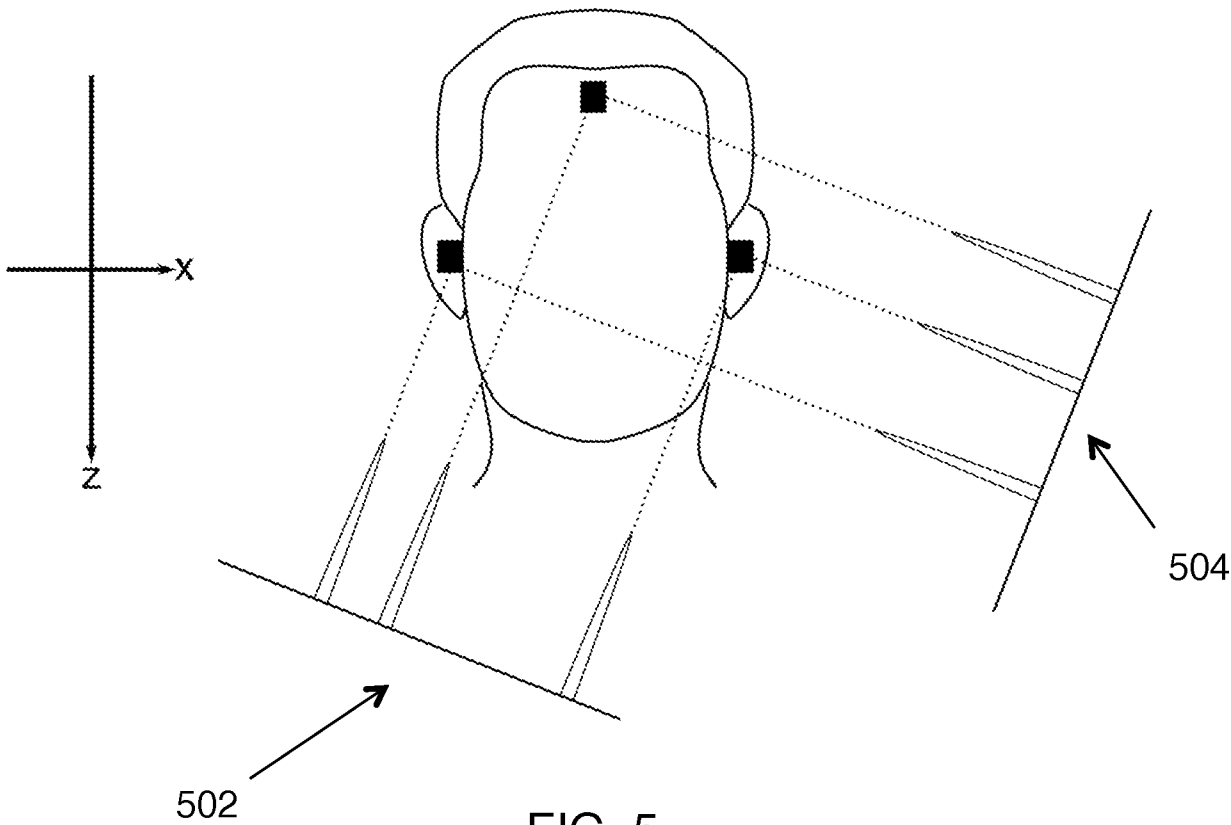


FIG. 5

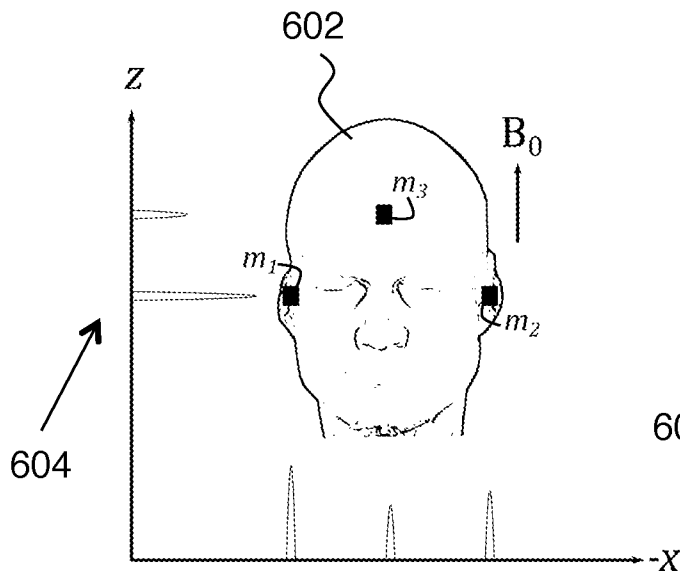


FIG. 6A

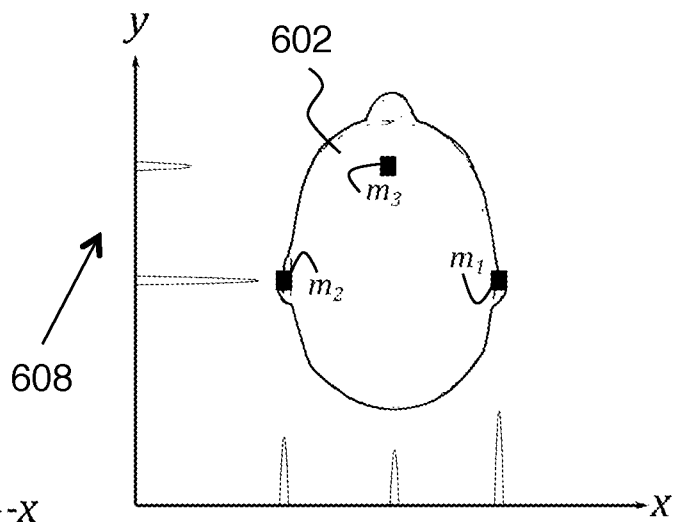


FIG. 6B

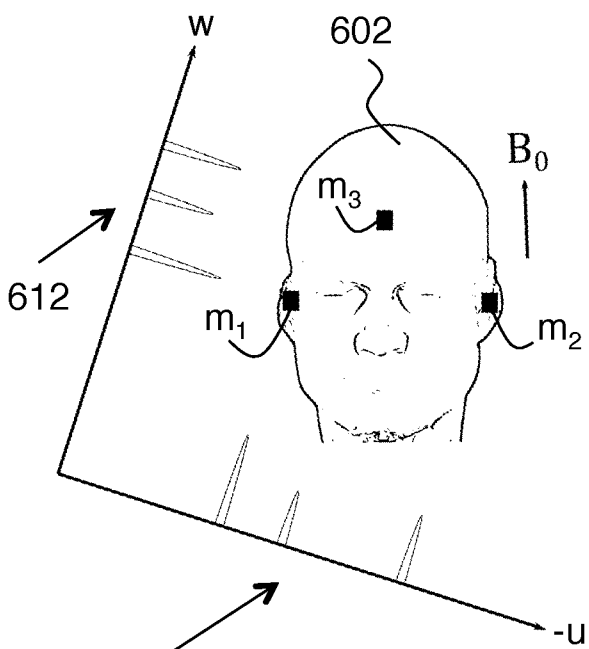


FIG. 6C

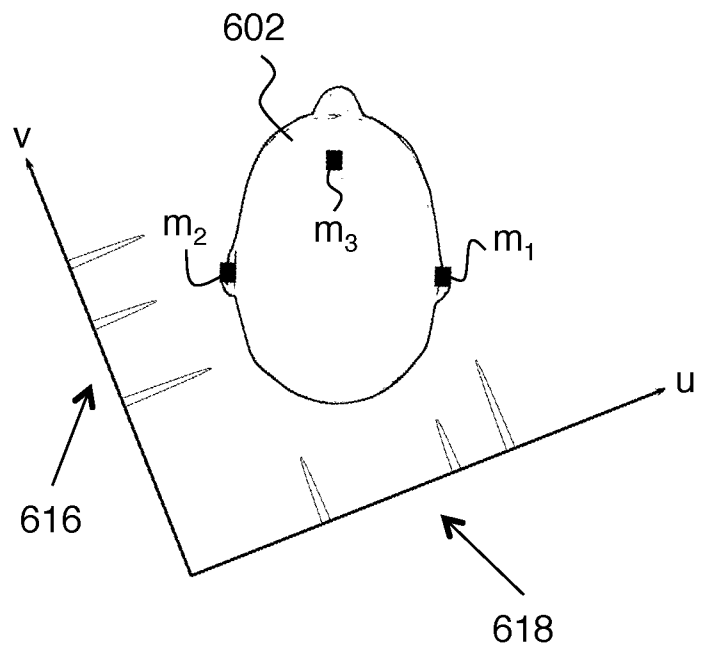


FIG. 6D

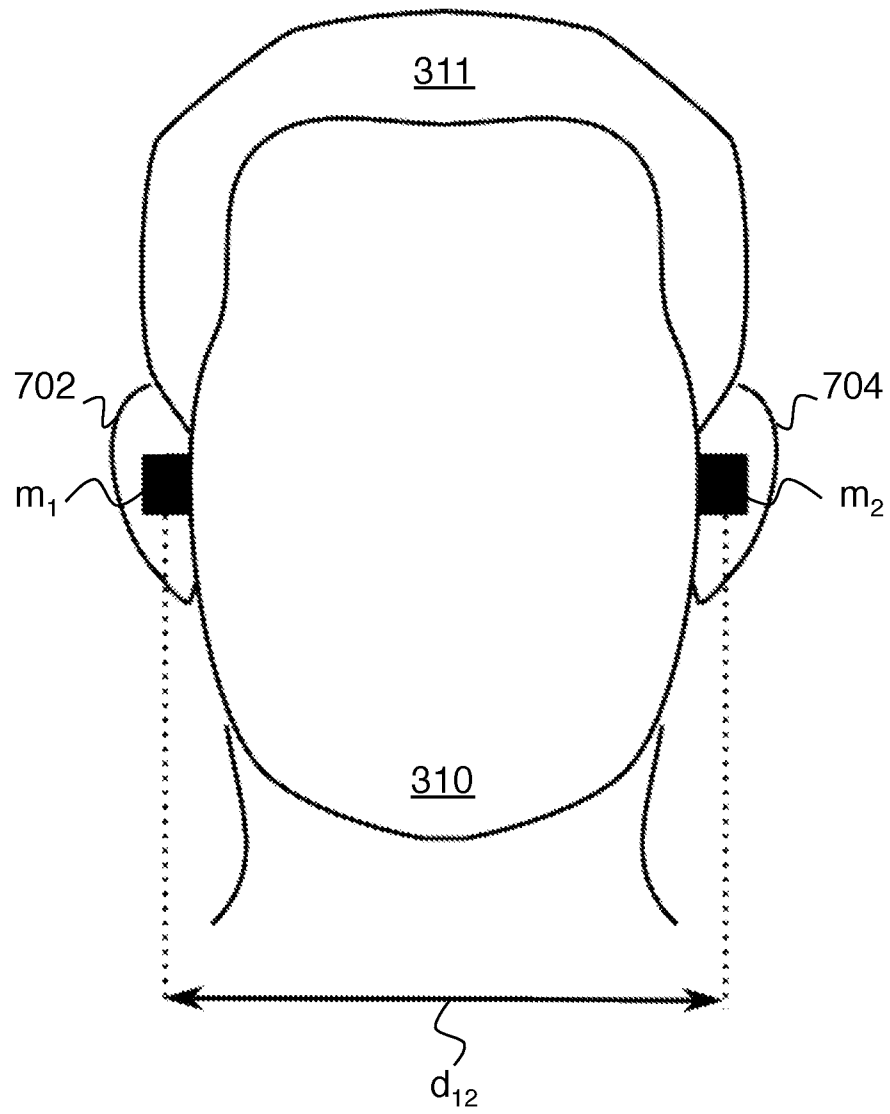


FIG. 7

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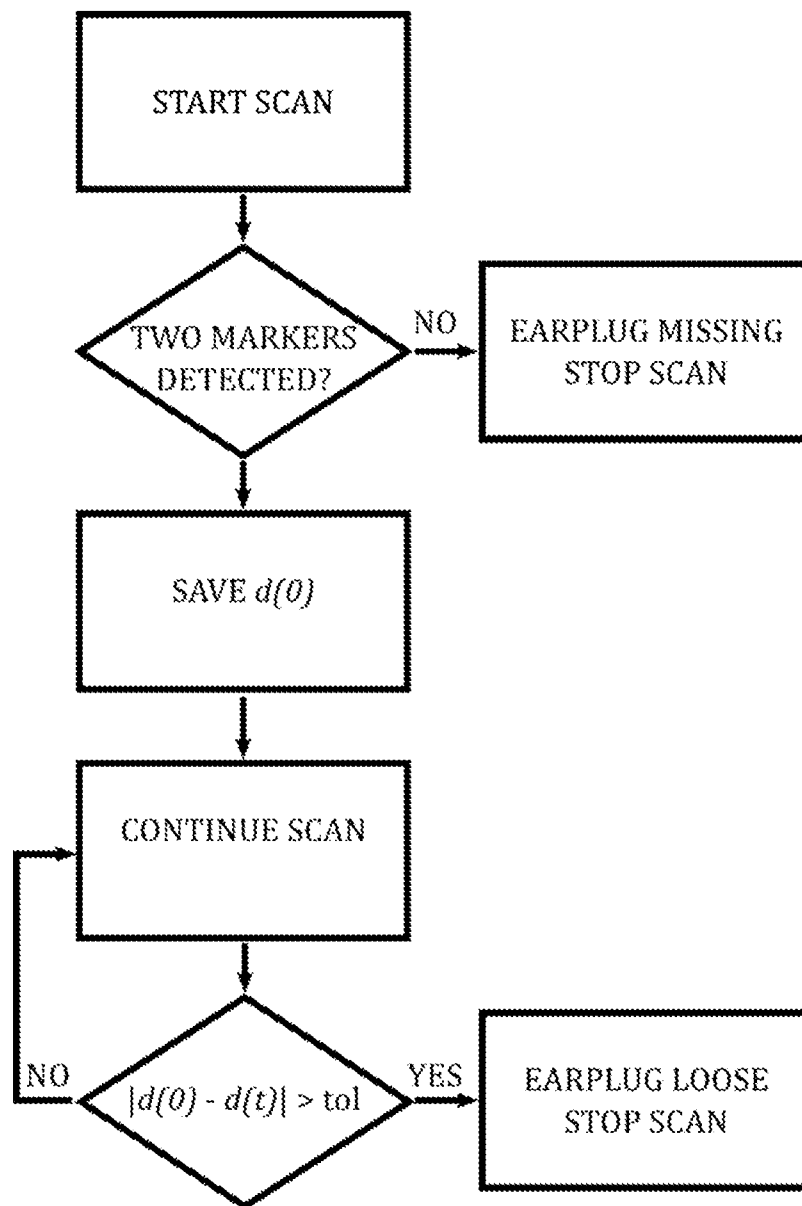


FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US16/28593

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - A61F11/08, A61B5/11, A61B5/055, A61B5/06 (2016.01)

CPC - A61F11/08, A61B5/11, A61B5/1127, A61B5/064, A61F11/08, A61B5/6817, A61B5/721, A61B90/39

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8): A61F11/08, A61B5/11, A61B5/055, A61B5/06 (2016.01); CPC: A61B5/062, A61B5/064, A61B5/11, A61B5/1127, A61B5/055, A61F11/08, A61B5/6817, A61B5/72, A61B5/7203, A61B5/7207, A61B5/721, A61B5/7214, A61B90/39, A61B2090/3954

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PatSeer (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, INPADOC Data); PubMed; EBSCO; Google/Google Scholar;
KEYWORDS: ear*, ear_plug, head, track*, mark*, movement, motion, MRI, MR, NMRI, magnetic, resonance, position, displacement, coil, wire, fiducials, correction, visib*, sample, frequency

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2014/0171784 A1 (THE BOARD OF TRUSTEES OF THE LELAND STANFORD JUNIOR UNIVERSITY) 19 June 2014; figures 1, 3C; paragraphs 31-33, 36-38	1-25
A	US 2014/0012127 A1 (BIBER, S et al.) 9 January 2014; figures 1-2; paragraphs 43, 46, 49, 62 78	1-25
A	US 6,419,680 B1 (COSMAN, E et al.) 16 July 2002; figure 1; column 1, lines 26-27, 44-53; column 2, lines 55-65; column 3, lines 1-30	1-25
A	US 2009/0209846 A1 (BAMMER, R) 20 August 2009; abstract; paragraphs 19, 31-32	1-25
A	US 2013/0188830 A1 (THE QUEEN'S MEDICAL CENTER et al.) 25 July 2013; entire document	1-25
A	US 2004/0171927 A1 (LOWEN, S et al.) 2 September 2004; entire document	1-25
A	WO 2014/116868 A1 (KINETICOR, INC) 31 July 2014; entire document	1-25

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

24 June 2016 (24.06.2016)

Date of mailing of the international search report

22 JUL 2016

Name and mailing address of the ISA/

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