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Magnetic resonance imaging magnet system
Magnetsystem für die bildgebende magnetische Resonanz
Système d’aimants pour l’imagerie par résonance magnétique

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EP-A- 0 619 499
US-A- 4 766 378
US-A- 5 250 901
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US-A- 4 827 235
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Description

[0001] The present invention relates to magnetic resonance imaging (MRI). It finds particular application in conjunction with open geometry magnet systems, and will be described with particular reference thereto.

[0002] One common type of MRI system has a patient receiving bore through which a main magnetic field is generated longitudinally by a surrounding series of annular magnet windings. A patient or subject is selectively translated axially along a horizontal central axis of the bore to have a region of interest positioned in an imaging volume for imaging. In these solenoid type annular bore systems, access to the patient for surgical and/or invasive procedures, physiological tests, equipment, and the like is limited and awkward. Moreover, such systems tend to be claustrophobic for some patients.

[0003] To provide for access and reduce the claustrophobic effect in patients, open or vertical field magnets have been developed. Open magnets typically include a ferrous flux return path in the form of a “C”, “H”, or four-poster arrangement. The flux return paths have an open gap or patient receiving region within which the patient or subject is disposed for imaging. Typically, two annular magnets are disposed on opposing sides of the gap to generate the main magnetic field or magnetic flux through. Due to the difference in the susceptibility of the flux return path and the air in the gap, there tends to be non-uniformity and other magnetic flux errors in the gap. However, high image quality is dependent on having the main magnetic field in the imaging volume as homogeneous and perturbation free as possible. In order to generate a stronger, more uniform magnetic flux through the gap, ferrous pole pieces are typically positioned at the ends of the flux return path on either side of the gap or patient receiving region. In some cases, the pole pieces are shaped and contoured with features such as annular ridges and grooves, as appropriate, to generate a more uniform or homogeneous magnetic flux between the pole pieces. For example, see US-A-5 436 607 and US-A-5 162 768 which show contoured and/or shaped pole pieces for enhancing the magnetic field in the imaging volume. In US-A-5 250 901 (disclosing an apparatus according to the preamble of claim 1) a high Tc superconductive electromagnet winding is used to increase the magnetic field homogeneity within the air gap of the magnet structure.

[0004] Although the use of contoured and/or shaped pole pieces has certain advantages, there are trade-offs. In particular, with reference to US-A-5 436 607, one trade-off is that the features are concentrated on the back sides of the poles so as not to reduce the patient gap. Poles with contour features on the front side thereof are considered advantageous over those having features on the back because contour features are generally more effective the closer they are to the imaging volume. At higher field strengths, to achieve the same level of effectiveness as at lower field strengths, the contoured features are more pronounced (i.e. the grooves are deeper, etc.). This sensitivity to position of pole shaping features allows some designs to be realized with poleface features that cannot be realized with shaping behind the pole. Further, in EP-A-0 619 499 a magnet comprising pair of pole pieces supported on a yoke is described. The pole pieces each include adjustable shim pieces comprising at least one annular ring, which can be positionally adjusted in a direction parallel to the longitudinal axis of the poles. A fixed and rigid separate pole plate is placed between the shim pieces and the gradient coils. The purpose of the adjustable shim pieces is to homogenise the magnetic field in the imaging volume, which is obviously performed empirically.

[0005] In accordance with one aspect of the present invention, an MRI scanner is provided. It includes a pair of opposing pole pieces disposed symmetrically about an imaging volume facing one another. The pair of opposing pole pieces includes a first ferrous pole piece having a front side facing the imaging volume and a back side. As well, a second ferrous pole piece also has a front side facing the imaging volume and a back side. A magnetic flux return path extends, remotely from the imaging volume, between a point adjacent the back side of the first pole piece and a point adjacent the back side of the second pole piece. A pair of annular primary magnets generate a magnetic flux through the imaging volume, the pair of opposing pole pieces, and the magnetic flux return path. The first and second pole piece are each circumferentially surrounded by a corresponding annular primary magnet of the pair of annular magnets. The back side of the first pole piece and the back side of the second pole piece each are distanced from the projections of the magnetic flux return path, so that the attractive force between the primary magnets is balanced against the attractive force between each magnet and its attraction to its magnetic image mirrored in the corresponding projection. A number of annular rings are integrated with the pair of opposing pole pieces for example with the front sides of the pole pieces, for homogenizing the magnetic flux through the imaging volume. The annular rings include a material having magnetic properties different than those of the pair of opposing pole pieces.

[0006] In accordance with another aspect of the present invention, the annular rings are made from permanently magnetized material. Further, the material from which the annular rings are made may be selected from a group consisting of neodymium boron iron, samarium cobalt, a cobalt iron alloy, a nickel iron alloy, and a cobalt steel alloy. Additionally, the material from which the annular rings are made may have a magnetic susceptibility different from that of the pair of opposing pole pieces.

[0007] Ways of carrying out the invention will now be described in detail, by way of example, with reference to the accompanying drawings, in which:

FIGURE 1 is a diagrammatic illustration of an MRI scanner in accordance with aspects of the present
invention; and

FIGURE 2 is a diagrammatic illustration of a front face of a pole piece in accordance with aspects of the present invention.

[0008] With reference to FIGURE 1, a magnetic resonance imaging scanner 10 includes annular primary magnets 12 and 12' which are disposed in a pair of parallel horizontal planes to define a patient gap 14 therebetween. Preferably, the magnets 12 and 12' are superconducting magnets. To this end, the magnets 12 and 12' are disposed in annular helium cans 16 and 16' that are surrounded by vacuum dewars 18 and 18'. Alternatively, resistive magnets are employed. A first or upper disk-shaped ferrous pole piece 20 is circumferentially surrounded by the annular magnet 12. Similarly, a second or lower disk-shaped ferrous pole piece 20' is circumferentially surrounded by the annular magnet 12'. The first and second pole pieces 20 and 20' have front sides 22 and 22', respectively, which face one another from across the patient receiving gap 14 through an imaging volume 24 located therein. Preferably, the upper and lower pole pieces 20 and 20' are symmetrical to one another, are symmetrical with respect to the imaging volume 24, and are circularly symmetrical with respect to a central vertical axis 26.

[0009] A couch (not shown) suspends a subject to be examined at least partially within the patient receiving gap 14 (i.e., so that a region of interest is in the imaging volume 24).

[0010] A magnetic flux return path 30 extends from a point adjacent a back side 28 of the first or upper pole piece 20 remotely from the imaging volume 24 to a point adjacent a back side 28' of the second or lower pole piece 20'. More specifically, the pole pieces 20 and 20' are disposed centrally in an RF room which is defined by or lined with iron, including a ceiling layer, a floor layer, and wall layers. The ceiling, floor, and wall layers are composed of multiple sections which are mechanically connected together to thereby form the magnetic flux return path 30.

[0011] In a preferred embodiment, the pole pieces 20 and 20' are displaced from one another by a distance 2A and are each displaced from the ceiling and floor iron layers, respectively, by a distance 1A. In this manner, each magnet 12 and 12' and pole piece 20 and 20' is attracted to the magnetic reflection of itself in the adjoining iron layer. By positioning the pole pieces 20 and 20' symmetrically between each other and the iron layer, the attractive force between the magnets 12 and 12' is balanced against the attractive force between each magnet and its attraction to its magnetic image mirrored in the floor and ceiling structure. The magnets 12 and 12' and the pole pieces 20 and 20' are positioned in the room such that the net axial magnetic forces on the coils and pole pieces 20 and 20' are substantially balanced. Of course, for patient safety, convenience in bringing the magnets 12 and 12' up to field, and supporting gravity weight, the pole pieces 20 and 20' and magnets 12 and 12' are supported to the ceiling and floor, respectively, by non-ferrous, non-magnetic support structures (not shown). Additionally, the support structures within the cryostats of the superconducting magnet assemblies are configured for minimal thermal conductivity to minimize heat loss but consistent with design parameters for safety, field energizing, weight, and residual forces due to misalignment.

[0012] In a preferred embodiment, the spacing of the magnetic flux return path 30 including the iron ceiling and floor layers is selected to be an appropriate height for the attending physicians and equipment positioned within the room, typically 240 cm or more. The spacing of the magnetic flux return path 30 adjacent the back sides 28 and 28' of the pole pieces 20 and 20', as discussed above, is preferably selected to be about twice the vertical dimension of the patient receiving gap 14. For a typical 65 cm gap, the ceiling and floor layers of the magnetic flux return path 30 include projections 32 and 34, respectively, which are spaced about 130 cm from each other. Of course, the projections 32 and 34 need not be the same. Rather, their relative projection is selected such that a horizontal centre of the patient receiving gap 14 is at a convenient height for attending physicians, attendants, and technicians.

[0013] For magnets 12 and 12' which generate a 0.5 T flux in the imaging volume 24 of the patient gap 14 and which are separated by about 65 cm from one another and about 32.5 cm from the ceiling and floor layers, a total flux through the magnetic flux return path 30 is about 1.0 Wb. To accommodate this flux, the projections 32 and 34 have a thickness of about 13 cm. At about 2 m out, the ceiling and floor layers can be tapered to about 8 cm. The wall layers, which vary with the dimension of the room, are selected to have sufficient thickness to provide radio frequency (RF) shielding, magnetic shielding, and a flux return path 30 which does not saturate, as well as providing support for the ceiling layer. A typical 0.5 T magnetically shielded room receives about 35 tons of iron, which is transported in sections or panels and assembled on site using conventional room-construction techniques.

[0014] With reference to FIGURE 2 and continuing reference to FIGURE 1, the ferrous pole pieces 20 and 20' operate to homogenize or otherwise make uniform the main magnetic field or magnetic flux through the imaging volume 24. To further their effectiveness in this regard, the pole pieces 20 and 20' are each integrated with an array of annular rings 40 and 40', respectively. The annular rings 40 and 40' are concentrically arranged on the front sides 22 and 22' of the first and second ferrous pole pieces 20 and 20'. The annular rings 40 and 40' are made of a material having magnetic properties different from those of the pole pieces 20 and 20'. In one approach, the annular hoops 40 and 40' are made from segments of permanently magnetized material. In this manner, a particular annular ring is magnetically aligned, or alter-
nately, anti-aligned, with the magnetic flux in the imaging volume, 24, such that the magnetic flux is concentrated, or alternately, reduced, in a region of the particular annular ring. Thereby, particular perturbations in the uniformity or homogeneity of the magnetic field through the imaging volume 24 are adjusted and/or eliminated. For those applications where magnetic fields in the vicinity of the poles 20 and 20' do not exceed about 1.0 T, appropriate materials for the permanent magnet annular rings 40 and 40' are neodymium boron iron, and the like. In a preferred method of construction, annular grooves are cut into the pole piece. The grooves are filled with powdered or pelletized permanently magnetized material bonded in place with a resin, such as epoxy, or contained in a tubular construction. Alternatively, hoop segments of permanently magnetized material, preferably sintered, are assembled in the grooves to define the rings. As another alternative, plates of the permanently magnetized material are loaded into the grooves.

In an alternative approach, instead of using a permanent magnet material for the annular rings 40 and 40', a material which is not permanently magnetised is used that has a different magnetic susceptibility than that of the pole pieces 20 and 20'. Appropriate materials for this alternate approach include a nickel iron alloy, a cobalt steel alloy, a cobalt iron alloy, samarium cobalt, and the like. Generally, this alternate approach is most advantageous when the magnetic fields in the vicinity of the pole pieces 20 and 20' approach 1.0 T and/or when used as part of, or near, a Rose shim. The exact diameter, width, size, arrangement, and number of the annular rings 40 and 40' is mathematically estimated and iteratively adjusted until the magnetic field through the imaging volume 24 is optimized. In a preferred embodiment, a non-linear finite element model is employed for the design process. It is to be appreciated that the diameter, width, size, arrangement, and number of annular rings 40 and 40' vary with the strength of the main magnetic field and the geometry of the magnets 12 and 12' and the pole pieces 20 and 20'. Furthermore, in addition to the annular rings 40 and 40', the surfaces of the ferrous pole pieces 20 and 20' are optionally shaped or contoured with ridges and air-filled grooves to achieve a further degree of uniformity in the magnetic flux through the imaging volume 24.

In operation, a source of magnetic flux generates the magnetic flux through the imaging volume 24, the pair of opposing pole pieces 20 and 20', and the magnetic flux return path 30. More specifically, a main magnetic field control 50 controls the superconducting magnets 12 and 12' positioned around the ferrous pole pieces 20 and 20' such that a substantially uniform, temporally constant main magnetic field is created along a z direction through the imaging volume 24. Alternately, the magnets 12 and 12' are resistive and/or are placed at other positions adjacent the magnetic flux return path 30 as desired for particular applications.

A magnetic resonance echo means operated under the control of a sequence control circuit 52 applies a series of RF and magnetic field gradient pulses to invert or excite magnetic spins, induce magnetic resonance, refocus magnetic resonance, manipulate magnetic resonance, spatially and otherwise encode the magnetic resonance, to saturate spins, and the like to generate MRI and spectroscopy sequences. More specifically, a gradient coil assembly 54 selectively creates magnetic gradients in the main magnetic field across the imaging volume 24 via gradient current amplifiers 56 that apply electrical current pulses to the gradient coil assembly 54. Preferably, the gradient coil assembly 54 includes self-shielded gradient coils for producing magnetic gradients along three mutually orthogonal directions, x, y, and z.

[0018] An RF transmitter 60 transmits radio frequency pulses or pulse packets to a whole-body RF coil 62 disposed adjacent the imaging volume 24 to transmit RF pulses into the imaging volume 24. A typical RF pulse is composed of a packet of immediately contiguous pulse segments of short duration which, taken together with each other and any applied gradients, achieve a selected magnetic resonance manipulation. The RF pulses are used to saturate, excite resonance, invert magnetization, refocus magnetization, or manipulate resonance in selected portions of the imaging volume 24. For whole-body applications, the resonance signals are commonly picked up by the whole-body RF coil 62. The RF coil may be disposed near the opposing pole pieces 20 and 20' (as is the whole-body RF coil 62 illustrated) on the patient or subject being examined. For example, a surface coil may be positioned contiguous to the patient or subject being examined for controllably inducing magnetic resonance in a selected region of the patient or subject.

[0019] A receiver 64 (preferably a digital receiver) receives signals from resonating dipoles. The signals are received via the same RF coil that transmits the radio frequency pulses. Alternately, separate receiver coils may be used. For example, receive-only surface coils may be disposed contiguous to a selected region of the patient or subject being examined to receive resonance induced therein by the whole-body RF transmitting coil 62. The sequence control circuit 52 controls the gradient pulse amplifiers 56 and the RF transmitter 60 to generate any of a plurality of multiple echo sequences, such as echo-planar imaging, echo-volume imaging, gradient and spin-echo imaging, fast spin-echo imaging, and the like. For the selected sequence, the receiver 64 receives a plurality of data inputs in rapid succession following each RF excitation pulse. Ultimately, the radio frequency signals received are demodulated and reconstructed into an image representation by a reconstruction processor 70 which applies a two-dimensional Fourier transform or other appropriate reconstruction algorithm. The image may represent a planar slice through the patient, an array of parallel planar slices, a three-dimensional volume, or the like. The image is then stored in an image memory 72 where it may be accessed by a display, such as a
video monitor 74 which provides a human-readable display of the resultant image.

[0020] One advantage of the imaging magnet with integrated poleface features described above is an improved pole piece for MRI scanners. Another advantage is improved homogeneity of the magnetic flux in the imaging volume. Another advantage is that openness is improved homogeneity of the magnetic flux in the imaging volume (24), the pair of opposing pole pieces (20, 20') are each circumferentially surrounded by a corresponding annular primary magnets (12, 12') is balanced against the attractive force between each magnet and its attraction to its magnetic image mirrored in the corresponding projection (32, 34); and that a number of annular rings (40, 40') are integrated with and arranged concentrically on the front sides (22, 22') of the opposing pole pieces (20, 20') for homogenizing the magnetic flux through the imaging volume (24), said annular rings (40, 40') including a material having magnetic properties different than that of the pair of opposing pole pieces (20, 20').

2. Magnetic resonance imaging apparatus as claimed in claim 1, wherein the annular rings (40, 40') are made from permanently magnetized material.

3. Magnetic resonance imaging apparatus as claimed in claim 2, wherein the material from which the annular rings (40, 40') are made is selected from a group consisting of neodymium iron boron, samarium cobalt, a cobalt iron alloy, a nickel iron alloy, and a cobalt steel alloy.

4. Magnetic resonance imaging apparatus as claimed in claim 1, wherein the material from which the annular rings (40, 40') are made has a magnetic susceptibility different from that of the pair of opposing pole pieces (20, 20').

**Patentansprüche**

1. Magnetresonanzbildgebungsgerät mit: einem Paar entgegengesetzter Polschuhe (20, 20'), die symmetrisch um ein Bildgebungsvolumen (24) herum angeregt sind und einander gegenüberliegen, wobei das genannte Paar entgegengesetzter Polschuhe (20, 20') einen ersten Polschuh (20) aus Eisen mit einer Vorderseite (22), die dem Bildgebungsvolumen (24) gegenüberliegt, und mit einer Rückseite (28) umfasst und einen zweiten Polschuh (20) aus Eisen mit einer Vorderseite (22), die dem Bildgebungsvolumen (24) gegenüberliegt, und mit einer Rückseite (28); einem magnetischen Rückflusspfad (30), der sich in einem Abstand vom Bildgebungsvolumen (24) befindet und von der Rückseite (28) des ersten Polschuh (20) zu der Rückseite (28) des zweiten Polschuh (20) erstreckt; einem Paar ringförmiger Primärmagneten, die einen magnetischen Fluss durch das Bildgebungsvolumen (24), das Paar von entgegengesetzten Polschuhen (20, 20') und den magnetischen Rückflusspfad (30) erzeugen; dadurch gekennzeichnet, dass der erste und der zweite Polschuh (20, 20') jeweils am Umfang von einem entsprechenden ringförmigen Primärmagneten (12, 12') des genannten Polschuh (20, 20') jeweils in einem Abstand von Vorsprüngen (32, 34) des magnetischen Rückflusspfads (30) befinden, so dass die Anziehungskraft zwischen den Primärmagneten (12, 12') durch die Anziehungskraft zwischen jedem Magnet und seine Anziehung zu seinem in dem entsprechenden Vorsprung (32, 34) gespiegelten Magnetbahn ausgeglichen wird; und dass eine Anzahl von ringförmigen Ringen (40, 40') mit den Vorderseiten (22, 22') der entgegengesetzten Polschuhe (20, 20') integriert und konzentrisch darauf angeordnet ist, um den magnetischen durch das Bildgebungsvolumen (24) homogen zu machen, wobei die ringförmigen Ringe (40, 40') ein Material mit magnetischen Eigenschaften umfassen, die sich von denjenigen des Paar der entgegengesetzten Polschu-
he (20, 20') unterscheiden.

2. Magnetresonanzbildgebungsgerät nach Anspruch 1, wobei die ringförmigen Ringe (40, 40') aus permanent magnetisiertem Material bestehen.


4. Magnetresonanzbildgebungsgerät nach Anspruch 1, wobei das Material, aus dem die ringförmigen Ringe (40, 40') hergestellt werden, eine magnetische Suszeptibilität aufweist, die sich von der des Paares der entgegengesetzten Polschuhe (20, 20') unterscheidet.

**Revendications**

1. Appareil d'imagerie par résonance magnétique comprenant une paire de pièces polaires opposées (20, 20') disposées symétriquement autour d'un volume de formation d'image (24) et se faisant face, ladite paire de pièces polaires opposées (20, 20') comprenant une première pièce polaire ferreuse (20) présentant un côté antérieur (22) qui fait face au volume de formation d'image (24) et un côté postérieur (28), et une seconde pièce polaire ferreuse (20') présentant un côté antérieur (22') qui fait face au volume de formation d'image (24) et un côté postérieur (28') ; un trajet de retour de flux magnétique (30) situé à une certaine distance du volume de formation d'image (24) et allant du côté postérieur (28) de la première pièce polaire (20) jusqu'au côté postérieure (28') de la seconde pièce polaire (20') ; une paire d'aimants primaires annulaires générant un flux magnétique à travers le volume de formation d'image (24), la paire de pièces polaires opposées (20, 20'), et le trajet de retour de flux magnétique (30) ; caractérisé en ce que la première et la seconde pièce polaire (20, 20') sont chacune entourées de manière circonférentielle par un aimant primaire annulaire correspondant (12, 12') de ladite paire d'aimants annulaires ; et que le côté postérieur (28) de la première pièce polaire (20) et le côté postérieur (28') de la seconde pièce polaire (20') sont chacun espaçés de saillies (32, 34) du trajet de retour de flux magnétique (30), de distances telles que la force d'attraction entre les aimants primaires (12, 12') soit équilibrée par rapport à la force d'attraction entre chaque aimant et son attraction vers son image magnétique réfléchie en miroir dans la saillie correspondante (32, 34) ; et qu'un certain nombre de bagues annulaires (40, 40') sont intégrées dans les côtés antérieurs (22, 22') des pièces polaires opposées (20, 20') et disposées concentriquement sur ceux-ci afin d'homogénéiser le flux magnétique à travers le volume de formation d'image (24), lesdites bagues annulaires (40, 40') comprenant un matériau ayant des propriétés magnétiques différentes de celles de la paire de pièces polaires opposées (20, 20').

2. Appareil d'imagerie par résonance magnétique suivant la revendication 1, dans lequel les bagues annulaires (40, 40') sont faites d'un matériau à aïmation permanente.

3. Appareil d'imagerie par résonance magnétique suivant la revendication 2, dans lequel le matériau dont les bagues annulaires (40, 40') sont faites est sélectionné dans un groupe comprenant du néodyme - fer - bore, du samarium - cobalt, un alliage fer - cobalt, un alliage fer - nickel, et un alliage acier - cobalt.

4. Appareil d'imagerie par résonance magnétique suivant la revendication 1, dans lequel le matériau dont les bagues annulaires (40, 40') sont faites possède une susceptibilité magnétique différente de celle de la paire de pièces polaires opposées (20, 20').