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MAGNETIC RESONANCE IMAGING APPARATUS AND MAGNETIC RESONANCE IMAGING METHOD

Abstract

A magnetic resonance imaging apparatus includes processing circuitry configured to collect a plurality of magnetic resonance signals while changing relative relationship between echoes and acquisition windows, and generate a magnetic resonance image based on data obtained by combining the plurality of magnetic resonance signals.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is based upon and claims the benefit of priority from Japanese Patent Application No. 2024-024902, filed Feb. 21, 2024, the entire contents of which are incorporated herein by reference.

FIELD

[0002] Embodiments described herein relate generally to a magnetic resonance imaging apparatus and a magnetic resonance imaging method.

BACKGROUND

[0003] In a magnetic resonance imaging apparatus, a reception band (band width) is mainly determined by a radio frequency (RF) coil and a sampling rate (SR). Widening of the reception band provides advantages such as reduction in data collection time, reduction in echo time (TE), and suppression of influence by chemical shift, motion artifact, and the like. Widening of the reception band further provides advantages such as widening of a field of view (FOV) when the RF coil is assumed to have a sufficient reception band.

[0004] Therefore, when a sampling interval is reduced and an effective sampling rate is increased, the reception band can be widened.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] FIG. **1** is a diagram illustrating a configuration example of a magnetic resonance imaging apparatus according to an exemplary embodiment;

[0006] FIG. **2** is a diagram illustrating an outline of processing performed by the magnetic resonance imaging apparatus according to the exemplary embodiment;

[0007] FIG. **3**A is a diagram illustrating a phantom used for verification of the processing performed by the magnetic resonance imaging apparatus according to the exemplary embodiment;

[0008] FIG. **3**B is a diagram illustrating an example of an image obtained by a first pulse sequence in the magnetic resonance imaging apparatus according to the exemplary embodiment;

[0009] FIG. **3**C is a diagram illustrating an example of an image obtained by a second pulse sequence in the magnetic resonance imaging apparatus according to the exemplary embodiment;

[0010] FIG. **3**D is a diagram illustrating an example of a combined image obtained in the magnetic resonance imaging apparatus according to the exemplary embodiment;

[0011] FIG. **4** is a flowchart illustrating an example of a flow of processing performed by a magnetic resonance imaging apparatus according to a first exemplary embodiment;

[0012] FIG. **5** is a diagram illustrating an example of a pulse sequence performed by the magnetic resonance imaging apparatus according to the first exemplary embodiment;

[0013] FIG. **6** is a diagram illustrating an example of a pulse sequence performed by the magnetic resonance imaging apparatus according to the first exemplary embodiment;

[0014] FIG. **7** is a flowchart illustrating an example of a flow of processing performed by a magnetic resonance imaging apparatus according to a second exemplary embodiment;

[0015] FIG. **8** is a diagram illustrating an example of a pulse sequence performed by the magnetic resonance imaging apparatus according to the second exemplary embodiment;

[0016] FIG. **9** is a diagram illustrating an example of a pulse sequence performed by a magnetic resonance imaging apparatus according to a third exemplary embodiment;

[0017] FIG. **10** is a diagram illustrating an example of a pulse sequence performed by the magnetic resonance imaging apparatus according to the third exemplary embodiment;

[0018] FIG. **11** is a diagram illustrating an example of a pulse sequence performed by the magnetic resonance imaging apparatus according to the third exemplary embodiment; and

[0019] FIG. **12** is a diagram illustrating an example of a pulse sequence performed by a magnetic resonance imaging apparatus according to a fourth exemplary embodiment.

DETAILED DESCRIPTION

[0020] A magnetic resonance imaging apparatus according to an exemplary embodiment includes processing circuitry configured to collect a plurality of magnetic resonance signals while changing relative relationship between echoes and acquisition windows, and generate a magnetic resonance image based on data obtained by combining the plurality of magnetic resonance signals.

[0021] Various Embodiments will be described hereinafter with reference to the accompanying drawings.

[0022] Exemplary embodiments of a magnetic resonance imaging apparatus and a magnetic resonance imaging method are described in detail below with reference to the drawings.

First Exemplary Embodiment

[0023] FIG. **1** is a block diagram illustrating a magnetic resonance imaging apparatus **100** according to a first exemplary embodiment. As illustrated in FIG. **1**, the magnetic resonance imaging apparatus **100** includes a static magnetic field magnet **101**, a static magnetic field power supply (not illustrated), a gradient magnetic field coil **103**, a gradient magnetic field power supply **104**, a patient table **105**, patient table control circuitry **106**, a transmission coil **107**, transmission circuitry **108**, a reception coil **109**, reception circuitry **110**, sequence control circuitry **120** (sequence control unit), and a computer **130** (also referred to as an “image processing apparatus”). A subject P (e.g., human body) is not included in the magnetic resonance imaging apparatus **100**. The configuration illustrated in FIG. **1** is merely an example. For example, the sequence control circuitry **120** and components in the computer **130** may be appropriately integrated or separated.

[0024] The static magnetic field magnet **101** is a magnet formed into a substantially cylindrical shape that is hollow inside, and generates a static magnetic field in an internal space. The static magnetic field magnet **101** is, for example, a superconducting magnet. Another example of the static magnetic field magnet **101** may be a permanent magnet.

[0025] The gradient magnetic field coil **103** is a coil formed into a substantially cylindrical shape that is hollow inside, and is disposed on an inner side of the static magnetic field magnet **101**. The gradient magnetic field coil **103** is formed by combining three coils corresponding to X, Y, and Z axes, which are orthogonal to one another. The three coils generate gradient magnetic fields that vary in magnetic field intensity along the X, Y, and Z axes, by individually receiving supply of a current from the gradient magnetic field power supply **104**. The gradient magnetic fields in the X, Y, and Z axes generated by the gradient magnetic field coil **103** are, for example, a slice gradient magnetic field Gs, a phase encoding gradient magnetic field Ge, and a readout gradient magnetic field Gr. The gradient magnetic field power supply **104** supplies the current to the gradient magnetic field coil **103**.

[0026] The patient table **105** includes a top board **105***a* on which the subject P is placed, and the top board **105***a* is inserted into a cavity (imaging port) of the gradient magnetic field coil **103** in a state where the subject P is placed under the control of the patient table control circuitry **106**. The patient table **105** is normally installed such that a longitudinal direction is parallel to a center axis of the static magnetic field magnet **101**. The patient table control circuitry **106** drives the patient table **105** and moves the top board **105***a* in the longitudinal direction and a vertical direction under the control of the computer **130**.

[0027] The transmission coil **107** is disposed on an inner side of the gradient magnetic field coil **103**, and generates a high-frequency magnetic field by receiving supply of a radio frequency (RF) pulse from the transmission circuitry **108**.

[0028] The transmission circuitry **108** includes a pulse generator, an RF generator, a modulator, and an RF amplifier, and supplies the RF pulse corresponding to a Larmor frequency defined by a type of an atom to be a target and magnetic field intensity, to the transmission coil **107**. The pulse generator generates a waveform of an RF pulse signal. The RF generator generates an RF signal of a resonance frequency. The modulator modulates an amplitude of the RF signal generated by the RF generator with the waveform generated by the pulse generator, thereby generating the RF pulse signal. The RF amplifier amplifies the RF pulse signal generated by the modulator and outputs the amplified RF pulse signal to the transmission coil **107**.

[0029] The reception coil **109** is disposed on an inner side of the gradient magnetic field coil **103**, and receives magnetic resonance signals (hereinafter, referred to as “MR signals” as necessary) emitted from the subject P due to influence of the high-frequency magnetic field. When receiving the magnetic resonance signals, the reception coil **109** outputs the received magnetic resonance signals to the reception circuitry **110**.

[0030] The transmission coil **107** and the reception coil **109** described above are merely examples. The transmission coil **107** and the reception coil **109** may each be composed of a single coil or a combination of a plurality of coils among a coil having a transmission function, a coil having a reception function, and a coil having a transmission and reception function.

[0031] The reception circuitry **110** detects the magnetic resonance signals output from the reception coil **109**, and generates magnetic resonance data based on the detected magnetic resonance signals. More specifically, the reception circuitry **110** performs digital conversion on the magnetic resonance signals output from the reception coil **109** to generate the magnetic resonance data. The reception circuitry **110** transmits the generated magnetic resonance data to the sequence control circuitry **120**. The reception circuitry **110** may be provided to a rack apparatus, which includes the static magnetic field magnet **101** and the gradient magnetic field coil **103**. Further, some functions of the reception circuitry **110**, for example, a digital conversion function of the magnetic resonance signals, may be provided to the reception coil **109**.

[0032] The sequence control circuitry **120** drives the gradient magnetic field power supply **104**, the transmission circuitry **108**, and the reception circuitry **110** based on sequence information transmitted from the computer **130**, thereby imaging the subject P. The sequence information is information defining a procedure for performing imaging. The sequence information defines intensity and a supply timing of the current supplied from the gradient magnetic field power supply **104** to the gradient magnetic field coil **103**, intensity and an application timing of the RF pulse supplied from the transmission circuitry **108** to the transmission coil **107**, a detection timing of the magnetic resonance signals by the reception circuitry **110**, and the like. For example, the sequence control circuitry **120** is integrated circuitry such as an application specific integrated circuit (ASIC) and a field programmable gate array (FPGA), or electronic circuitry such as a central processing unit (CPU) and a micro processing unit (MPU). Details of a pulse sequence performed by the sequence control circuitry **120** are described below.

[0033] The sequence control circuitry **120** drives the gradient magnetic field power supply **104**, the RF amplifier through the transmission circuitry **108**, and the reception circuitry **110**, thereby imaging the subject P. As a result, when receiving the magnetic resonance data from the reception circuitry **110**, the sequence control circuitry **120** transfers the received magnetic resonance data to the computer **130**. For example, the sequence control circuitry **120** two-dimensionally or three-dimensionally arranges the magnetic resonance data received from the reception circuitry **110**, based on positional information imparted by the readout gradient magnetic field, the phase encoding gradient magnetic field, and the slice gradient magnetic field, thereby storing the magnetic resonance data as data configuring a k-space in a memory **132** as a storage unit.

[0034] The computer **130** performs control of the entire magnetic resonance imaging apparatus **100**, generation of an image, and the like. The computer **130** includes the memory **132**, an input device **134**, a display **135**, and processing circuitry **150**. The processing circuitry **150** includes an interface function **131**, a control function **133**, and a generation function **136**.

[0035] In the first exemplary embodiment, processing functions performed by the interface function **131**, the control function **133**, and the generation function **136** are each stored in a form of program executable by a computer, in the memory **132**. The processing circuitry **150** is a processor that implements functions corresponding to respective programs by reading the programs from the memory **132** and executing the programs. In other words, the processing circuitry **150** in a state of having read the programs has the functions illustrated in the processing circuitry **150** in FIG. **1**. In FIG. **1**, description is given by assuming that the single processing circuitry **150** implements the processing functions performed by the interface function **131**, the control function **133**, and the generation function **136**; however, a plurality of independent processors may be combined to constitute the processing circuitry **150**, and the processors may execute the programs to implement the functions. In other words, each of the above-described functions may be configured as a program, and one piece of processing circuitry **150** may execute each program. In another example, a specific function may be implemented in dedicated independent program execution circuitry. In FIG. **1**, the interface function **131**, the control function **133**, and the generation function **136** are respectively examples of a reception unit, a control unit, and a generation unit. The sequence control circuitry **120** is an example of a sequence control unit.

[0036] The term “processor” used in the above description refers to circuitry such as a central processing unit (CPU), a graphical processing unit (GPU), an application specific integrated circuit (ASIC), and a programmable logic device (e.g., simple programmable logic device (SPLD), complex programmable logic device (CPLD), and field programmable gate array (FPGA)). The processor implements the functions by reading the programs stored in the memory **132** and executing the programs.

[0037] In place of storing the programs in the memory **132**, the programs may be directly incorporated in circuitry of the processor. In this case, the processor implements the functions by reading the programs incorporated in the circuitry and executing the programs. Each of the patient table control circuitry **106**, the transmission circuitry **108**, the reception circuitry **110**, and the like is also realized by electronic circuitry such as the above-described processor.

[0038] The processing circuitry **150** transmits the sequence information to the sequence control circuitry **120** and receives the magnetic resonance data from the sequence control circuitry **120** by using the interface function **131**. When receiving the magnetic resonance data, the processing circuitry **150** including the interface function **131** stores the received magnetic resonance data in the memory **132**.

[0039] The magnetic resonance data stored in the memory **132** is arranged in the k-space by the control function **133**. As a result, the memory **132** stores k-space data.

[0040] The memory **132** stores the magnetic resonance data received by the processing circuitry **150** including the interface function **131**, the k-space data arranged in the k-space by the processing circuitry **150** including the control function **133**, image data generated by the processing circuitry **150** including the generation function **136**, and the like. For example, the memory **132** is a semiconductor memory element such as a random access memory (RAM) and a flash memory, a hard disk, or an optical disk.

[0041] The input device **134** receives various kinds of instructions and information input from an operator. The input device **134** is, for example, a pointing device such as a mouse and a track ball, a selection device such as a mode selection switch, or an input device such as a keyboard. The display **135** displays a graphical user interface (GUI) for receiving input of an imaging condition, an image generated by the processing circuitry **150** including the generation function **136**, and the like under the control of the processing circuitry **150** including the control function **133**. The display **135** is a display device such as a liquid crystal display.

[0042] The processing circuitry **150** controls the entire magnetic resonance imaging apparatus **100** and controls imaging, generation of an image, display of an image, and the like by using the control function **133**. For example, the processing circuitry **150** including the control function **133** receives input of the imaging condition (e.g., imaging parameters) on the GUI, and generates the sequence information based on the received imaging condition. The processing circuitry **150** including the control function **133** transmits the generated sequence information to the sequence control circuitry **120**. The processing circuitry **150** reads the k-space data from the memory **132** and performs reconstruction processing such as Fourier transform on the read k-space data to generate an image, by using the generation function **136**.

[0043] The configuration has been described in which, as illustrated in FIG. **1**, the magnetic resonance imaging apparatus **100** according to the exemplary embodiment includes two magnets between which the subject is sandwiched or the cylindrical magnet; however, the magnetic resonance imaging apparatus **100** according to the exemplary embodiment is not limited to such a configuration. It is assumed that the magnetic resonance imaging apparatus **100** performs imaging in a region where a static magnetic field is uniform; however, the magnetic resonance imaging apparatus **100** may be used for a technique in which a region having distribution of the static magnetic field is used as an imaging region. A configuration having distribution of the static magnetic field may be, for example, a configuration including only one of the two magnets between which the subject is sandwiched. In a case where the configuration includes the cylindrical magnet, a region where the distribution of the static magnetic field is nonuniform near an opening of a bore may be used as the imaging region.

[0044] A background according to the exemplary embodiment is briefly described.

[0045] In the magnetic resonance imaging apparatus, a reception band (band width) is mainly determined by a RF coil and a sampling rate (SR). Widening of the reception band provides advantages such as reduction in data collection time, reduction in echo time (TE), and suppression of influence by chemical shift, motion artifact, and the like. Widening of the reception band further provides advantages such as widening of a field of view (FOV) when the RF coil is assumed to have a sufficient reception band. When a sampling interval is reduced and an effective sampling rate is increased, the reception band can be widened.

[0046] In consideration of such a background, the magnetic resonance imaging apparatus according to the exemplary embodiment includes the sequence control unit and the generation unit. The sequence control unit collects a plurality of magnetic resonance signals while changing relative relationship between an echo and an acquisition window. The generation unit generates a magnetic resonance image based on data obtained by combining the plurality of magnetic resonance signals.

[0047] A magnetic resonance imaging method according to the exemplary embodiment includes collecting a plurality of magnetic resonance signals while changing relative relationship between an echo and an acquisition window, and generating a magnetic resonance image based on data obtained by combining the plurality of magnetic resonance signals.

[0048] FIG. **2** illustrates an outline of such an idea. The sequence control circuitry **120** performs a pulse sequence a plurality of times. In FIG. **2**, the sequence control circuitry **120** performs a first pulse sequence **10***a* corresponding to first collection AD**1**, and a second pulse sequence **10***b* corresponding to second collection AD**2**. A collection period **15** and a collection period **16** are data collection periods corresponding to the first pulse sequence **10***a* and the second pulse sequence **10***b*, respectively. Sampling points **1***a*, **1***b*, **1***c*, and **1***d* each indicate a data point collected during the collection period **15** of the first pulse sequence **10***a*. Sampling points **2***a*, **2***b*, **2***c*, and **2***d* each indicate a data point collected during the collection period **16** of the second pulse sequence **10***b*. Each sampling point corresponds to, for example, data of one point in the k-space. A sampling interval SR **13** indicates a time interval of sampling. The sampling rate is increased as the sampling interval SR **13** is reduced.

[0049] In the pulse sequence performed the plurality of times, the sequence control circuitry **120** performs collection while relatively shifting an echo and an acquisition window AW. For example, the sequence control circuitry **120** performs collection while shifting a timing of the acquisition window AW by an interval **14** that is ½ of the sampling interval SR **13** between the first pulse sequence **10***a* and the second pulse sequence **10***b*. Subsequently, after data collection, as illustrated in a lower part in FIG. **2**, the sequence control circuitry **120** combines data obtained by the first pulse sequence **10***a* and data obtained by the second pulse sequence **10***b* in the k-space to generate combined data **17**, and performs image reconstruction based on the combined data **17**.

[0050] As described above, the sequence control circuitry **120** can improve the sampling rate in a pseudo manner by shifting the echo by a time interval smaller than the sampling interval SR. For example, the sequence control circuitry **120** can widen a collection band width to N times by shifting the timing of the acquisition window AW by 1/N of the sampling interval SR.

[0051] FIGS. **3**A to **3**D illustrate examples of an image obtained by the method according to the exemplary embodiment. FIG. **3**A illustrates a phantom subjected to imaging, and a region **29** is a field of view (FOV). The sequence control circuitry **120** has acquired data twice by shifting the timings of the echo and the acquisition window AW. An image **26** illustrated in FIG. **3**B is an image obtained by reconstructing the data obtained by the first pulse sequence **10***a*. An image **27** illustrated in FIG. **3**C is an image obtained by reconstructing the data obtained by the second pulse sequence **10***b*. An image **28** illustrated in FIG. **3**D is an image obtained by combining the data obtained by the first pulse sequence **10***a* and the data obtained by the second pulse sequence **10***b* and then reconstructing the combined data. As illustrated, when collection is performed a plurality of times while shifting the timings of the echo and the acquisition window AW, the sampling rate can be effectively increased. Further, the sampling interval can be effectively shortened by half. Thus, the band width is increased, and imaging can be performed on the wider FOV.

[0052] The exemplary embodiment is described in more detail with reference to FIGS. **4** to **6**. FIG. **4** is a flowchart illustrating a flow of processing performed by the magnetic resonance imaging apparatus **100** according to the first exemplary embodiment.

[0053] First, in step S**100**A, the sequence control circuitry **120** collects the plurality of magnetic resonance signals while changing relative relationship between the echo and the acquisition window. The sequence control circuitry **120** collects the plurality of magnetic resonance signals while changing the relative relationship between the echo and the acquisition window AW by shifting the acquisition window AW by a width smaller than the sampling interval SR.

[0054] FIG. **5** illustrates an example in a case where the pulse sequence performed by the sequence control circuitry **120** is a pulse sequence of a spin echo (SE). The first pulse sequence **10***a* performed by the sequence control circuitry **120** in step S**100**A includes a 90-degree pulse **20**, a 180-degree pulse **21**, and an acquisition window AW **23***a*. After a TE **22** is elapsed from application of the 90-degree pulse **20**, an echo **25** is generated. The second pulse sequence **10***b* performed by the sequence control circuitry **120** includes the 90-degree pulse **20**, the 180-degree pulse **21**, and an acquisition window AW **23***b*. After the TE **22** is elapsed from application of the 90-degree pulse **20**, the echo **25** is generated. At this time, the sequence control circuitry **120** shifts the acquisition window AW **23***b* from the acquisition window AW **23***a* by a period **24** equivalent to ½ of the sampling interval SR. In this manner, the sequence control circuitry **120** collects the plurality of magnetic resonance signals while changing the relative relationship between the echo and the acquisition window. In this embodiment, the 90-degree pulse is described as an example of an excitation pulse, but a pulse with a flip angle other than 90 degrees can also be used. In this embodiment, the 180-degree pulse is described as an example of a refocusing pulse, but pulses with flip angles other than 180 degrees can also be used.

[0055] FIG. **6** illustrates an example in a case where the pulse sequence performed by the sequence control circuitry **120** is a pulse sequence of a field echo (FE). The first pulse sequence **10***a* performed by the sequence control circuitry **120** in step S**100**A includes the 90-degree pulse **20** and the acquisition window AW **23***a*. After the TE **22** is elapsed from application of the 90-degree pulse **20**, the echo **25** is generated. The second pulse sequence **10***b* performed by the sequence control circuitry **120** includes the 90-degree pulse **20** and the acquisition window AW **23***b*. After the TE **22** is elapsed from application of the 90-degree pulse **20**, the echo **25** is generated. At this time, the sequence control circuitry **120** shifts the acquisition window AW **23***b* from the acquisition window

AW **23***a* by the period **24** equivalent to ½ of the sampling interval SR. In this manner, the sequence control circuitry **120** collects the plurality of magnetic resonance signals while changing the relative relationship between the echo and the acquisition window.

[0056] Description is again provided with reference to FIG. **4**. In step S**200**, the processing circuitry **150** generates, by using the generation function **136**, a magnetic resonance image based on the data obtained by combining the plurality of magnetic resonance signals.

[0057] In the examples illustrated in FIG. **5** and FIG. **6**, the sequence control circuitry **120** collects the plurality of magnetic resonance signals twice while changing the relative relationship between the echo and the acquisition window; however, the exemplary embodiment is not limited thereto. The sequence control circuitry **120** may collect the plurality of magnetic resonance signals while shifting an acquisition window AW by 1/N of the sampling interval, where N is a natural number. Thus, the sequence control circuitry **120** can collect the plurality of magnetic resonance signals while widening the collection band width of the magnetic resonance signals to N times as compared with a case where collection of the plurality of magnetic resonance signals is performed once.

[0058] As described above, in the first exemplary embodiment, the sequence control circuitry **120** collects the plurality of magnetic resonance signals while changing the relative relationship between the echo and the acquisition window AW by shifting the acquisition window AW. As a result, the sampling rate can be effectively increased. Further, the sampling interval can be effectively shortened. Thus, the band width is increased, and imaging can be performed on the wider FOV.

Second Exemplary Embodiment

[0059] In the first exemplary embodiment, the case is described where the sequence control circuitry **120** collects the plurality of magnetic resonance signals while changing the relative relationship between the echo and the acquisition window by shifting the acquisition window by the width smaller than the sampling interval. In a second exemplary embodiment, a case is described where, in the pulse sequence of the spin echo, the relative relationship between the echo and the acquisition window is changed by shifting an application timing of a 180-degree pulse by a width smaller than the sampling interval. FIG. **7** is a flowchart illustrating a flow of processing performed by the magnetic resonance imaging apparatus **100** according to the second exemplary embodiment.

[0060] First, in step S**100**B, the sequence control circuitry **120** collects the plurality of magnetic resonance signals while changing the relative relationship between the echo and the acquisition window. In the second exemplary embodiment, the sequence control circuitry **120** performs the pulse sequence for generating the spin echo, and collects the plurality of magnetic resonance signals while changing the relative relationship between the echo and the acquisition window AW by shifting the application timing of the 180-degree pulse in the pulse sequence by a width smaller than the sampling interval.

[0061] FIG. **8** illustrates such an example. The first pulse sequence **10***a* performed by the sequence control circuitry **120** in step S**100**B includes the 90-degree pulse **20**, a 180-degree pulse **21***a*, and an acquisition window AW **23**. After the TE **22** is elapsed from application of the 90-degree pulse **20**, an echo **25***a* is generated. The second pulse sequence **10***b* performed by the sequence control circuitry **120** includes the 90-degree pulse **20**, a 180-degree pulse **21***b*, and the acquisition window AW **23**. After the TE **22** is elapsed from application of the 90-degree pulse **20**, an echo **25***b* is generated. At this time, the sequence control circuitry **120** shifts the application timing of the 180-degree pulse **21***b* from the application timing of the 180-degree pulse **21***a* by a period **30** equivalent to ½ of the sampling interval SR. Along with a shift between the application timing of the 180-degree pulse **21***a* and the application timing of the 180-degree pulse **21***b*, a shift **31** occurs between a generation time of the echo **25***a* and a generation time of the echo **25***b*. In this manner, the sequence control circuitry **120** collects the plurality of magnetic resonance signals while changing the relative relationship between the echo and the acquisition window.

[0062] Description is again provided with reference to FIG. **7**. In step S**200**, the processing circuitry **150** generates, by using the generation function **136**, a magnetic resonance image based on the data obtained by combining the plurality of magnetic resonance signals.

[0063] In the example illustrated in FIG. **7**, the case is described where the sequence control circuitry **120** collects the plurality of magnetic resonance signals twice while changing the relative relationship between the echo and the acquisition window; however, the exemplary embodiment is not limited thereto. The sequence control circuitry **120** may collect the plurality of magnetic resonance signals while shifting the application timing of the 180-degree pulse by 1/N of the sampling interval, where N is a natural number. Thus, the sequence control circuitry **120** can collect the plurality of magnetic resonance signals while widening the collection band width of the magnetic resonance signals to N times as compared with the case where collection of the plurality of magnetic resonance signals is performed once.

[0064] As described above, in the second exemplary embodiment, the sequence control circuitry **120** collects the plurality of magnetic resonance signals while changing the relative relationship between the echo and the acquisition window AW by shifting the application timing of the 180-degree pulse by the width smaller than the sampling interval SR. As a result, as in the first exemplary embodiment, the sampling rate can be effectively increased. Further, the sampling interval can be effectively shortened. Thus, the band width is increased, and imaging can be performed on the wider FOV.

[0065] In the first exemplary embodiment, the case is described where the sequence control circuitry **120** collects the plurality of magnetic resonance signals while changing the relative relationship between the echo and the acquisition window by shifting the acquisition window by the width smaller than the sampling interval. In the second exemplary embodiment, the case is described where, in the pulse sequence of the spin echo, the relative relationship between the echo and the acquisition window is changed by shifting the application timing of the 180-degree pulse by the width smaller than the sampling interval. The two exemplary embodiments can be combined.

[0066] More specifically, the sequence control circuitry **120** may collect the plurality of magnetic resonance signals while changing the relative relationship between the echo and the acquisition window by shifting the acquisition window by the width smaller than the sampling interval and shifting the application timing of the 180-degree pulse in the pulse sequence by the width smaller than the sampling interval. For example, the sequence control circuitry **120** performs collection by shifting the acquisition window AW by ¼ of the sampling interval SR and shifting the application timing of the 180-degree pulse by ¼ of the sampling interval SR. In this manner, both the acquisition window AW and the application timing of the 180-degree pulse are shifted, which makes it possible to effectively shorten the sampling interval while maintaining a small shift amount of each of the acquisition window AW and the application timing of the 180-degree pulse.

Third Exemplary Embodiment

[0067] In the first exemplary embodiment and the second exemplary embodiment, the case is described where the sequence control circuitry **120** performs the pulse sequence of a single echo. In a third exemplary embodiment, however, the pulse sequence is not limited thereto, and the sequence control circuitry **120** may perform a pulse sequence having multiple echoes.

[0068] FIG. **9** illustrates an example of a pulse sequence in a case where the plurality of magnetic resonance signals is collected by shifting the acquisition window AW by a width smaller than the sampling interval. A pulse sequence **10** is an exemplary configuration of the pulse sequence at one time among a plurality of times the pulse sequence is performed. The pulse sequence **10** is a pulse sequence having multiple echoes in which a plurality of 180-degree pulses **40**_a_, **40**_b_, **40**_c_, and **40**_d_ is applied relative to one 90-degree pulse **20**, and therefore, a plurality of echoes **50**_a_, **50**_b_, **50**_c_ and **50**_d_ is generated. Acquisition windows AW **51**_a_, **51**_b_, **51**_c_, and **51**_d_ are acquisition windows corresponding to the respective echoes.

[0069] In step S**100**A, the sequence control circuitry **120** performs a plurality of pulse sequences while simultaneously shifting the acquisition windows AW **51***a*, **51***b*, **51***c*, and **51***d* by a period **52**, which is shorter than the sampling interval SR, in each of the pulse sequences. For example, the sequence control circuitry **120** performs N pulse sequences while simultaneously shifting the acquisition windows AW **51***a*, **51***b*, **51***c*, and **51***d* by the period **52** equivalent to 1/N of the sampling interval SR in each of the pulse sequences. In this manner, the sequence control circuitry **120** collects the plurality of magnetic resonance signals while changing the relative relationship between the echo and the acquisition window. In step S**200**, the processing circuitry **150** generates, by using the generation function **136**, a magnetic resonance image based on the data obtained by combining the plurality of magnetic resonance signals.

[0070] FIG. **10** illustrates an example of a sequence in a case where the plurality of magnetic resonance signals is collected by shifting the application timing of the 180-degree pulse by a width smaller than the sampling interval SR. As in FIG. **9**, the pulse sequence **10** is an exemplary configuration of the pulse sequence at one time among a plurality of times the pulse sequence is performed. The pulse sequence **10** is a pulse sequence having multiple echoes in which a plurality of 180-degree pulses **41***a*, **41***b*, **41***c*, and **41***d* is applied relative to one 90-degree pulse **20**, and therefore, a plurality of echoes **60***a*, **60***b*, **60***c*, and **60***d* is generated. The acquisition windows AW **51***a*, **51***b*, **51***c*, and **51***d* are acquisition windows corresponding to the respective echoes.

[0071] In step S**100**A, the sequence control circuitry **120** performs a plurality of pulse sequences while simultaneously shifting the application timings of the 180-degree pulses by a period **53**, which is shorter than the sampling interval SR, in each of the pulse sequences. For example, the sequence control circuitry **120** performs N pulse sequences while simultaneously shifting the application timings of the 180-degree pulses by the period **53** equivalent to 1/N of the sampling interval SR in each of the pulse sequences. When the application timings of the 180-degree pulses are each shifted by the period **53**, timings of generated echoes are each shifted by a period **54**. In this manner, the sequence control circuitry **120** collects the plurality of magnetic resonance signals while changing the relative relationship between the echo and the acquisition window AW. In step S**200**, the processing circuitry **150** generates, by using the generation function **136**, a magnetic resonance image based on the data obtained by combining the plurality of magnetic resonance signals.

[0072] In the examples illustrated in FIG. **9** and FIG. **10**, the case is described where the relative relationship between the echo and the acquisition window AW is not changed in one pulse sequence; however, the exemplary embodiment is not limited thereto. The sequence control circuitry **120** may collect the plurality of magnetic resonance signals while changing the relative relationship between each of echoes constituting multi-echo and the acquisition window AW.

[0073] FIG. **11** illustrates such an example. In the example illustrated in FIG. **11**, in a pulse sequence **70**, the relative relationship between the echo and the acquisition window AW is changed. The pulse sequence **70** is a pulse sequence having multiple echoes in which a plurality of 180-degree pulses **40***a*, **40***b*, and **40***c* is applied relative to one 90-degree pulse **20**, and therefore, a plurality of echoes **50***a*, **50***b*, and **50***c* is generated. Acquisition windows AW **70**, **71**, and **72** are acquisition windows corresponding to the respective echoes.

[0074] In step S**100**A, the sequence control circuitry **120** performs the pulse sequence **70** while shifting the acquisition windows AW **71** and **72** from the acquisition window AW **70** by periods **81** and **82**, which are shorter than the sampling interval SR. As a result, positions in the k-space where data collection with the acquisition windows AW **71** and **72** is performed are shifted from a position in the k-space where the data collection is performed with the acquisition window AW **70**. For example, when it is assumed that data points of the k-space data collected by the acquisition window AW **70** are data points **74***a*, **74***b*, and **74***c*, data points of the k-space data collected by the acquisition window AW **71** are data points **73***a*, **73***b*, and **73***c*, and data points of the k-space data collected by the acquisition window AW **72** are data points **75***a*, **75***b*, and **75***c*. The processing circuitry **150** can generate, by using the generation function **136**, a magnetic resonance image based on the data obtained by combining the magnetic resonance signals.

[0075] As described above, in the third exemplary embodiment, the case where the pulse sequence having multiple echoes is performed is described. Therefore, even in the pulse sequence having multiple echoes, the sampling rate can be effectively increased. Further, the sampling interval can be effectively shortened. Thus, the band width is increased, and imaging can be performed on the wider FOV.

Fourth Exemplary Embodiment

[0076] In a fourth exemplary embodiment, a case is described where, in a pulse sequence of a field echo, the sequence control circuitry **120** changes relative positional relationship between the echo and the acquisition window by shifting an application timing of a readout gradient magnetic field by a width smaller than the sampling interval.

[0077] FIG. **12** illustrates an example in a case where the pulse sequence performed by the sequence control circuitry **120** is the pulse sequence of a field echo (FE), and the relative positional relationship between the echo and the acquisition window AW is changed by shifting the application timing of the readout gradient magnetic field. A first pulse sequence **90***a* performed by the sequence control circuitry **120** in step S**100**A includes an a-degree pulse **91** and an acquisition window AW **95***a*. After the TE **22** is elapsed from application of the a-degree pulse **91**, an echo **94***a* is generated by influence of readout gradient magnetic fields **92***a* and **92***b*. A second pulse sequence **90***b* performed by the sequence control circuitry **120** includes the a-degree pulse **91** and an acquisition window AW **95***b*, and an echo **94***b* is generated by influence of readout gradient magnetic fields **93***a* and **93***b*. At this time, the sequence control circuitry **120** collects the plurality of magnetic resonance signals by changing the relative relationship between the echo and the acquisition window AW by shifting an application timing of the readout gradient magnetic field **93***b* by a width smaller than the sampling interval. In step S**200**, the processing circuitry **150** generates, by using the generation function **136**, a magnetic resonance image based on the data obtained by combining the plurality of magnetic resonance signals.

[0078] In FIG. **12**, for simplification, a waveform of the readout gradient magnetic field **93***b* is illustrated so as to straightly rise; however, an actual waveform of the readout gradient magnetic field **93***b* includes rounding and overshoot. In other words, in the exemplary embodiment, shifting of the application timing of the readout gradient magnetic field **93***b* is not limited to a case where a rising timing of the readout gradient magnetic field **93***b* is changed. A time of the center of the echo **94***b* is determined by an integrated value of the readout gradient magnetic fields **93***a* and **93***b* applied by that time, and the echo **94***b* is generated when an integrated value of intensity on a negative side of the readout gradient magnetic field **93***a* and an integrated value of intensity on a positive side of the readout gradient magnetic field **93***b* are equal to each other. Accordingly, in actuality, the sequence control circuitry **120** controls the time of the echo **94***b* by controlling not only the rising time of the readout gradient magnetic field **93***b* but also the entire waveforms of the readout gradient magnetic field **93***a* and the readout gradient magnetic field **93***b*.

[0079] As described above, in the fourth exemplary embodiment, the case is described where the application timing of the readout gradient magnetic field is controlled. By controlling the application timing of the readout gradient magnetic field, the sampling rate can be effectively increased.

[0080] In the fourth exemplary embodiment, the case is described where the sampling rate is effectively increased by controlling the application timing of the readout gradient magnetic field. The fourth exemplary embodiment can be combined with the first exemplary embodiment and the second exemplary embodiment. The sampling rate can be effectively increased by further controlling, for example, the acquisition window and the application timing of the 180-degree pulse.

[0081] According to at least one of the exemplary embodiments described above, the data can be collected while the effective sampling rate is increased.
[0082] While certain embodiments have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the inventions. Indeed, the novel embodiments described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the embodiments described herein may be made without departing from the spirit of the inventions. The accompanying claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the inventions.

Claims

1. A magnetic resonance imaging apparatus, comprising processing circuitry configured to: collect a plurality of magnetic resonance signals while changing relative relationship between echoes and acquisition windows; and generate a magnetic resonance image based on data obtained by combining the plurality of magnetic resonance signals.
2. The magnetic resonance imaging apparatus according to claim 1, wherein the processing circuitry is configured to collect the plurality of magnetic resonance signals while changing the relative relationship by shifting the acquisition windows by a width smaller than a sampling interval.
3. The magnetic resonance imaging apparatus according to claim 2, wherein the processing circuitry is configured to perform a pulse sequence of a spin echo or a field echo.
4. The magnetic resonance imaging apparatus according to claim 2, wherein the processing circuitry is configured to collect the plurality of magnetic resonance signals while widening a collection band width of the magnetic resonance signals to N times as compared with a case where collection of the plurality of magnetic resonance signals is performed once, by shifting the acquisition windows by 1/N of the sampling interval, where N is a natural number.
5. The magnetic resonance imaging apparatus according to claim 1, wherein the processing circuitry is configured to perform a pulse sequence for generating a spin echo and to collect the plurality of magnetic resonance signals while changing the relative relationship by shifting an application timing of a refocusing pulse in the pulse sequence by a width smaller than a sampling interval.
6. The magnetic resonance imaging apparatus according to claim 5, wherein the processing circuitry is configured to widen a collection band width of the magnetic resonance signals to N times as compared with a case where collection of the magnetic resonance signals is performed once, by collecting the plurality of magnetic resonance signals while shifting the application timing of the refocusing pulse by 1/N of the sampling interval, where N is a natural number.
7. The magnetic resonance imaging apparatus according to claim 5, wherein the processing circuitry is configured to collect the plurality of magnetic resonance signals while changing the relative relationship by further shifting the acquisition windows by a width smaller than the sampling interval.
8. The magnetic resonance imaging apparatus according to claim 1, wherein the processing circuitry is configured to collect the plurality of magnetic resonance signals while changing the relative relationship by shifting an application timing of a readout gradient magnetic field by a width smaller than a sampling interval.
9. The magnetic resonance imaging apparatus according to claim 1, wherein the processing circuitry is configured to perform a pulse sequence having multiple echoes.
10. The magnetic resonance imaging apparatus according to claim 9, wherein the processing circuitry is configured to collect the plurality of magnetic resonance signals while changing the relative relationship for each echo constituting the multiple echoes

11. A magnetic resonance imaging method, comprising: collecting a plurality of magnetic resonance signals while changing relative relationship between echoes and acquisition windows; and generating a magnetic resonance image based on data obtained by combining the plurality of magnetic resonance signals.