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(54) Titre : SYSTEME ET PROCEDE POUR DISPOSITIF D'HYPERPOLARISATION A POLARISATION INDUITE PAR
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MAGNETIQUE (IRM) ET DE RESONANCE MAGNETIQUE NUCLEAIRE (RMN)
(54) Title: SYSTEM AND METHOD FOR MICROFLUIDIC PARAHYDROGEN INDUCED POLARIZATION
HYPERPOLARIZER FOR MAGNETIC RESONANCE IMAGING (MRI) AND NUCLEAR MAGNETIC RESONANCE
(NMR) APPLICATIONS

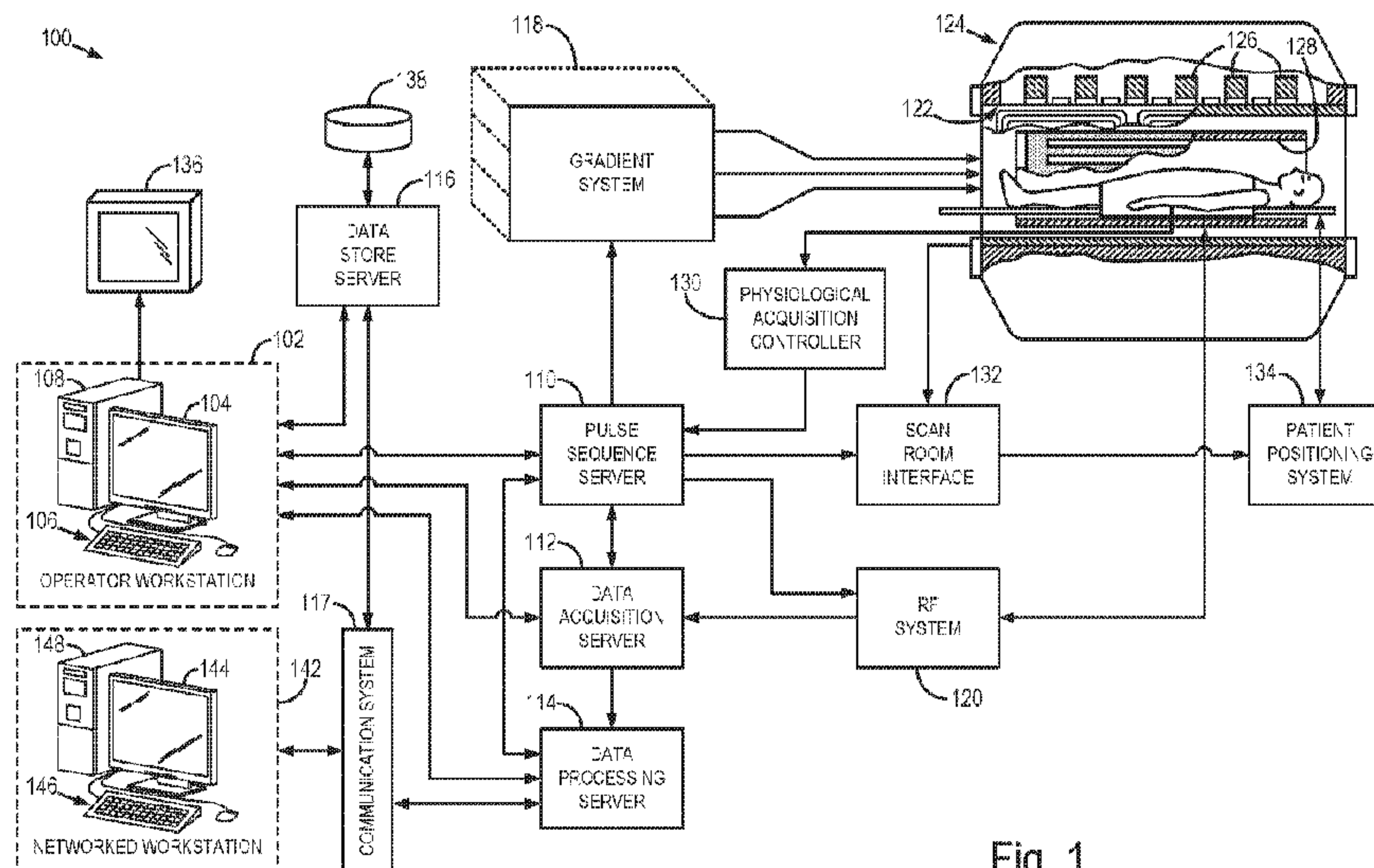


Fig. 1

(57) **Abrégé/Abstract:**

Systems and methods are provided for producing hyperpolarized materials for use during a magnetic resonance imaging (MRI) or nuclear magnetic resonance (NMR) process. The system and methods include the use of microfluidic and/or microreactor methods in one or more of the stages of parahydrogen production, enriched substrate production, and spin order transfer from the parahydrogen to a substrate.

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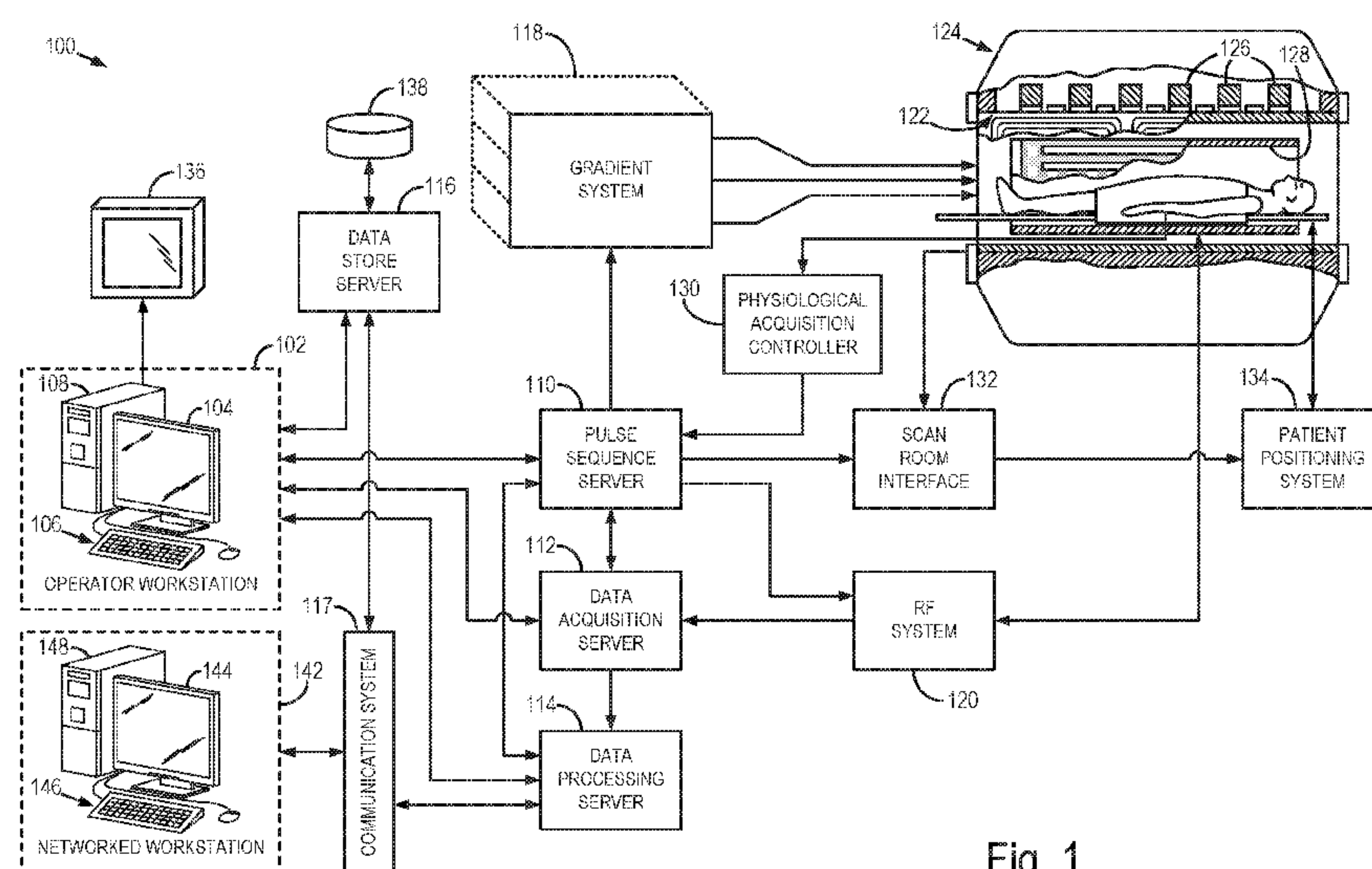


Fig. 1

(57) Abstract: Systems and methods are provided for producing hyperpolarized materials for use during a magnetic resonance imaging (MRI) or nuclear magnetic resonance (NMR) process. The system and methods include the use of microfluidic and/or microreactor methods in one or more of the stages of parahydrogen production, enriched substrate production, and spin order transfer from the parahydrogen to a substrate.

[Continued on next page]

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**SYSTEM AND METHOD FOR
MICROFLUIDIC PARAHYDROGEN INDUCED POLARIZATION
HYPERPOLARIZER FOR MAGNETIC RESONANCE IMAGING (MRI) AND
NUCLEAR MAGNETIC RESONANCE (NMR) APPLICATIONS**

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application Serial No. 62/372,554, filed on August 9, 2016, and entitled "SYSTEM AND METHOD FOR MICROFLUIDIC PARAPHYDROGEN INDUCED POLARIZATION HYPERPOLARIZER FOR MAGNETIC RESONANCE IMAGING (MRI) AND NUCLEAR MAGNETIC RESONANCE (NMR) APPLICATIONS."

FIELD

[0002] The present disclosure relates to systems and methods for creating materials for magnetic resonance imaging (MRI) or nuclear magnetic resonance (NMR) methods and systems. More particularly, the disclosure relates to a system and method for hyperpolarized magnetic resonance agents using microfluidic and microreactor technologies.

BACKGROUND

[0003] When a substance such as human tissue is subjected to a uniform magnetic field (polarizing field B_0), the individual magnetic moments of the excited nuclei in the tissue attempt to align with this polarizing field, but precess about it in random order at their characteristic Larmor frequency. If the substance, or tissue, is subjected to a magnetic field (excitation field B_1) which is in the x-y plane and which is near the Larmor frequency, the net aligned moment, M_z , may be rotated, or "tipped", into the x-y plane to produce a net transverse magnetic moment M_t . A signal is emitted by the excited nuclei or "spins", after the excitation signal B_1 is terminated, and this signal may be received and processed to form an image.

[0004] When utilizing these "MR" signals to produce images, magnetic field gradients (G_x , G_y , and G_z) are employed. Typically, the region to be imaged is scanned by a sequence of measurement cycles in which these gradients vary according to the particular localization method being used. The resulting set of received MR signals are digitized and processed to reconstruct the image using one of many well known reconstruction techniques.

[0005] Molecular imaging includes a variety of imaging modalities and

employs techniques that detect molecular events such as cell signaling, gene expression, and pathologic biomarkers. These techniques seek to achieve early detection of diseases, better management of therapy treatment, and improved monitoring of cancer recurrence. MRI and NMR provide specific advantages for molecular imaging applications, due to its noninvasive nature. Traditional molecular MRI and NMR techniques rely on the administration of a contrast agent to a designated location within a subject. Oftentimes, a site-specific contrast agent is employed that interacts with a given molecule of interest. These conventional techniques, however, exhibit poor sensitivity, making the detection of the contrast agents difficult. This is especially true when imaging the brain, which has a natural barrier to exogenous chemicals.

[0006] Hyperpolarization is the nuclear spin polarization of a material far beyond thermal equilibrium conditions, which may be applied to gases such as ^{129}Xe and ^3He , and small molecules where the polarization levels can be enhanced by a factor of 10^4 - 10^5 above thermal equilibrium levels. Hyperpolarized noble gases are typically used in MRI of the lungs. Hyperpolarized small molecules are typically used for in-vivo metabolic imaging. For example, a hyperpolarized metabolite can be injected into animals or patients and the metabolic conversion can be tracked in real-time.

[0007] Hyperpolarization of long-lived nuclei including ^{13}C and ^{15}N offers the intriguing possibility to develop tracers for diagnostic MRI with superior properties to existing Lanthanide based relaxation agents. Unlike lanthanide agents such as Gd-DTPA where the toxic relaxation agent must be wrapped in a large protective chelate that limits its properties, ^{13}C and ^{15}N labeling can be performed on a wide range of organic chemicals appropriate for probing blood flow, permeability, molecular transport, and metabolism. These agents have the added advantage of almost zero background signal in the body and the potential to detect chemical conversion by chemical shift, or frequency, measurement. This ability to observe chemical conversion is absent in nuclear medicine studies.

[0008] Despite the promise of hyperpolarized MR agents, progress in translation has been slow. Part of the problem is the need for local production of the transiently hyperpolarized tracer. The technology involves low temperatures, catalysts or free radical agents, and then ultimately a time limited injection. One of the available technologies is called Dynamic Nuclear Polarization (DNP)

hyperpolarization. DNP systems have been used to provide hyperpolarized pyruvate for initial human trials. DNP has the advantage of chemical simplicity but the technique involves very low temperatures and a very strong magnet that make it a poor candidate for miniaturization, cost reduction, and widespread use. First in human results have been demonstrated with this technology, however, and excitement is sufficient that numerous top academic institutions have installed or will soon install systems.

[0009] Therefore, hyperpolarization continues to develop as an important technique to increase contrast in MRI. It would be desirable to have systems and methods that are efficient, safe, and inexpensive to produce hyperpolarized contrast agents for MRI.

SUMMARY

[0010] The present disclosure overcomes the aforementioned drawbacks by providing a flexible, efficient, and ultimately low-cost PHIP hyperpolarized tracer production system using principles of microfluidics and microreactors.

[0011] In accordance with one aspect of the disclosure, a system is disclosed that includes a parahydrogen production system, which includes a microreactor that processes hydrogen into parahydrogen based on a request from a magnetic resonance imaging (MRI) or nuclear magnetic resonance (NMR) system. The system further includes a hyperpolarization and conversion system including a spin transfer device that receives the processed hydrogen from the microreactor and transfers spin order from the processed hydrogen to a substrate.

[0012] In accordance with another aspect of the disclosure, a method for producing polarized hydrogen is disclosed that includes at least the following steps. First, a micro hydrogen generator in a polarization delivery system generates hydrogen. A microreactor in the polarization delivery system processes the hydrogen into parahydrogen based on the request. A spin transfer device receives processed hydrogen from the microreactor. The spin transfer device transfers spin order from the processed hydrogen to a substrate.

[0013] In accordance with yet another aspect of the disclosure, a method for producing contrast agent for a magnetic resonance imaging (MRI) process is disclosed that includes using a polarization delivery system. First, a request is generated based on a subject to be scanned in the MRI system. A micro hydrogen

generator in the polarization delivery system then generates hydrogen based on the request. A microreactor in the polarization delivery system processes the hydrogen into parahydrogen based on the request. A spin transfer device receives processed hydrogen from the microreactor. The spin transfer device transfers spin order from the processed hydrogen to produce the contrast agent to be injected to the subject.

[0014] In accordance with still another aspect of the disclosure, an imaging system is provided that includes a magnetic resonance imaging (MRI) or nuclear magnetic resonance (NMR) system configured to perform an MRI or NMR process to acquire imaging data from a subject to be scanned in the MRI or NMR system during the MRI or NMR process. The imaging system also includes a hyperpolarization system comprising a spin transfer device that receives hydrogen and transfers spin order from the hydrogen to a substrate and a computer system. The computer system is configured to develop a pulse sequence to carry out the MRI or NMR process generate a request for processed hydrogen to be received from the hyperpolarization system to carry out the MRI or NMR process, carry out the MRI or NMR process using the pulse sequence to acquire the imaging data from the subject having received the processed hydrogen, and reconstruct an image of the subject using the imaging data.

[0015] In accordance with another aspect of the disclosure, a microfluidic or microreactor polarization delivery system is provided. The system includes a parahydrogen production system comprising a microfluidic or microreactor that processes hydrogen based on a request from a magnetic resonance imaging (MRI) or nuclear magnetic resonance (NMR) system. The system also includes a hyperpolarization and conversion system comprising a spin transfer device that receives the processed hydrogen from the microfluidic or microreactor and transfers spin order from the processed hydrogen to a substrate.

[0016] In accordance with yet another aspect of the disclosure, a method for parahydrogen production for imaging is disclosed that includes processing hydrogen using a microfluidic or microreactor based on a request from a magnetic resonance imaging (MRI) or nuclear magnetic resonance (NMR) system and receiving the processed hydrogen from the microfluidic or microreactor and transferring spin order from the processed hydrogen to a substrate.

[0017] The foregoing and other advantages of the disclosure will appear from

the following description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] Fig. 1 is a block diagram of an MRI system which employs the present disclosure.

[0019] Fig. 2 is a block diagram illustrating an example polarization delivery system.

[0020] Fig. 3A is an example flow chart setting forth steps of a first method for producing hyperpolarized agents in accordance with the present disclosure.

[0021] Fig. 3B is an example flow chart setting forth steps of a second method for producing hyperpolarized agents in accordance with the present disclosure.

[0022] Fig. 3C is an example flow chart setting forth steps of a third method for producing hyperpolarized agents in accordance with the present disclosure.

[0023] Fig. 3D is an example flow chart setting forth steps of a fourth method for producing hyperpolarized agents in accordance with the present disclosure.

DETAILED DESCRIPTION

[0024] Referring particularly now to Fig. 1, an example of a magnetic resonance imaging (MRI) system 100 is illustrated. Though an MRI system is illustrated, one of skill will readily appreciate that the systems and methods of the present disclosure are likewise applicable to or nuclear magnetic resonance (NMR), magnetic resonance spectroscopy (MRS), and the like. Thus, as used herein, "MRI" should not be understood to be limited to imaging applications and can be more generally understood to include other resonance-based investigative techniques, including NMR, MRS, and the like.

[0025] The MRI system 100 includes an operator workstation 102, which will typically include a display 104, one or more input devices 106, such as a keyboard and mouse, and a processor 108. The processor 108 may include a commercially available programmable machine running a commercially available operating system. The operator workstation 102 provides the operator interface that enables scan prescriptions to be entered into the MRI system 100. In general, the operator workstation 102 may be coupled to four servers: a pulse sequence server 110; a data acquisition server 112; a data processing server 114; and a data store server 116. The operator workstation 102 and each server 110, 112, 114, and 116 are

connected to communicate with each other. For example, the servers 110, 112, 114, and 116 may be connected via a communication system 117, which may include any suitable network connection, whether wired, wireless, or a combination of both. As an example, the communication system 117 may include both proprietary or dedicated networks, as well as open networks, such as the internet.

[0026] The pulse sequence server 110 functions in response to instructions downloaded from the operator workstation 102 to operate a gradient system 118 and a radiofrequency (“RF”) system 120. Gradient waveforms necessary to perform the prescribed scan are produced and applied to the gradient system 118, which excites gradient coils in an assembly 122 to produce the magnetic field gradients G_x , G_y , and G_z used for position encoding magnetic resonance signals. The gradient coil assembly 122 forms part of a magnet assembly 124 that includes a polarizing magnet 126 and a whole-body RF coil 128.

[0027] RF waveforms are applied by the RF system 120 to the RF coil 128, or a separate local coil (not shown in Fig. 1), in order to perform the prescribed magnetic resonance pulse sequence. Responsive magnetic resonance signals detected by the RF coil 128, or a separate local coil (not shown in Fig. 1), are received by the RF system 120, where they are amplified, demodulated, filtered, and digitized under direction of commands produced by the pulse sequence server 110. The RF system 120 includes an RF transmitter for producing a wide variety of RF pulses used in MRI pulse sequences. The RF transmitter is responsive to the scan prescription and direction from the pulse sequence server 110 to produce RF pulses of the desired frequency, phase, and pulse amplitude waveform. The generated RF pulses may be applied to the whole-body RF coil 128 or to one or more local coils or coil arrays (not shown in Fig. 1).

[0028] The RF system 120 also includes one or more RF receiver channels. Each RF receiver channel includes an RF preamplifier that amplifies the magnetic resonance signal received by the coil 128 to which it is connected, and a detector that detects and digitizes the I and Q quadrature components of the received magnetic resonance signal. The magnitude of the received magnetic resonance signal may, therefore, be determined at any sampled point by the square root of the sum of the squares of the I and Q components:

$$M = \sqrt{I^2 + Q^2}$$

Eqn. 1;

and the phase of the received magnetic resonance signal may also be determined according to the following relationship:

$$\varphi = \tan^{-1}\left(\frac{Q}{I}\right)$$

Eqn. 2.

[0029] The pulse sequence server 110 also optionally receives patient data from a physiological acquisition controller 130. By way of example, the physiological acquisition controller 130 may receive signals from a number of different sensors connected to the patient, such as electrocardiograph (“ECG”) signals from electrodes, or respiratory signals from a respiratory bellows or other respiratory monitoring device. Such signals are typically used by the pulse sequence server 110 to synchronize, or “gate,” the performance of the scan with the subject’s heart beat or respiration.

[0030] The pulse sequence server 110 also connects to a scan room interface circuit 132 that receives signals from various sensors associated with the condition of the patient and the magnet system. It is also through the scan room interface circuit 132 that a patient positioning system 134 receives commands to move the patient to desired positions during the scan.

[0031] The digitized magnetic resonance signal samples produced by the RF system 120 are received by the data acquisition server 112. The data acquisition server 112 operates in response to instructions downloaded from the operator workstation 102 to receive the real-time magnetic resonance data and provide buffer storage, such that no data is lost by data overrun. In some scans, the data acquisition server 112 does little more than passing the acquired magnetic resonance data to the data processor server 114. However, in scans that require information derived from acquired magnetic resonance data to control the further performance of the scan, the data acquisition server 112 is programmed to produce such information and convey it to the pulse sequence server 110. For example, during prescans, magnetic resonance data is acquired and used to calibrate the pulse sequence performed by the pulse sequence server 110. As another example, navigator signals may be acquired and used to adjust the operating parameters of the RF system 120 or the gradient system 118, or to control the view order in which

k-space is sampled. In still another example, the data acquisition server 112 may also be employed to process magnetic resonance signals used to detect the arrival of a contrast agent in a magnetic resonance angiography (MRA) scan. By way of example, the data acquisition server 112 acquires magnetic resonance data and processes it in real-time to produce information that is used to control the scan.

[0032] The data processing server 114 receives magnetic resonance data from the data acquisition server 112 and processes it in accordance with instructions downloaded from the operator workstation 102. Such processing may, for example, include one or more of the following: reconstructing two-dimensional or three-dimensional images by performing a Fourier transformation of raw k-space data; performing other image reconstruction algorithms, such as iterative or backprojection reconstruction algorithms; applying filters to raw k-space data or to reconstructed images; generating functional magnetic resonance images; calculating motion or flow images; and so on.

[0033] Images reconstructed by the data processing server 114 are conveyed back to the operator workstation 102 where they are stored. Real-time images are stored in a data base memory cache (not shown in Fig. 1), from which they may be output to operator display 112 or a display 136 that is located near the magnet assembly 124 for use by attending physicians. Batch mode images or selected real time images are stored in a host database on disc storage 138. When such images have been reconstructed and transferred to storage, the data processing server 114 notifies the data store server 116 on the operator workstation 102. The operator workstation 102 may be used by an operator to archive the images, produce films, or send the images via a network to other facilities.

[0034] The MRI system 100 may also include one or more networked workstations 142. By way of example, a networked workstation 142 may include a display 144; one or more input devices 146, such as a keyboard and mouse; and a processor 148. The networked workstation 142 may be located within the same facility as the operator workstation 102, or in a different facility, such as a different healthcare institution or clinic.

[0035] The networked workstation 142, whether within the same facility or in a different facility as the operator workstation 102, may gain remote access to the data processing server 114 or data store server 116 via the communication system 117.

Accordingly, multiple networked workstations 142 may have access to the data processing server 114 and the data store server 116. In this manner, magnetic resonance data, reconstructed images, or other data may exchange between the data processing server 114 or the data store server 116 and the networked workstations 142, such that the data or images may be remotely processed by a networked workstation 142. This data may be exchanged in any suitable format, such as in accordance with the transmission control protocol (TCP), the internet protocol (IP), or other known or suitable protocols.

[0036] Fig. 2 is a block diagram illustrating an example polarization delivery system 200. The system 200 is a flexible and efficient system that produces tracers using principles of microfluidics and microreactors. For example, the system 200 may be based on continuous flow microfluidic methods, which have revolutionized chemical synthesis and typically provide superior consistency, simplicity, efficiency, and purity to batch synthesis methods. Such methods are particularly suitable to synthesis where high pressures, large surface areas, extreme temperatures or potentially dangerous ingredients are necessary. Since PHIP hyperpolarization may involve small quantities of potentially explosive hydrogen gas, require temperatures less than 50K if parahydrogen is produced locally, and can benefit from high pressure and large surface areas for the spin transfer or hydrogenation process, the use of microfluidic and microreactor methods may be very beneficial. Here, the hydrogen is put in a high spin order, parahydrogen state. However, it actually has zero net magnetization (or polarization).

[0037] In Fig. 2, the polarization delivery system 200 includes a parahydrogen production system 210 that produces parahydrogen. The polarization delivery system 200 further includes a substrate production system 220 that produces substrates. Both the parahydrogen production system 210 and the substrate production system 220 send output to the hyperpolarization and conversion system 230, which transfers spin order to the tracer. The whole polarization delivery system 200 may be a mobile system that can be easily controlled and moved by professionals in hospitals. The polarization delivery system 200 may also include an injector or infusion system 240, such that it infuses tracers into a subject in a MRI system 100 (or nuclear magnetic resonance (NMR)). Note that the polarization delivery system 200 need not include the parahydrogen production system 210 and the substrate production system 220 locally in one or more embodiments especially

when the two systems 210 and 220 are very bulky. However, the polarization delivery system 200 can produce parahydrogen locally based on one or more requests, for example, from an MRI or nuclear magnetic resonance (NMR) that may be connected thereto and produce substrates to carry the parahydrogen for the specific subject when the two systems 210 and 220 are locally connected to the conversion system 230.

[0038] The parahydrogen production system 210 may work at temperatures below 50K so that the produced parahydrogen becomes the thermodynamically preferred state. After heating, the gas only very slowly loses its para state depending on the presence of oxygen and other trace molecules. Remote production of parahydrogen may be possible since its lifetime may be at least several weeks in an appropriately clean pressurized tank. However, local production has the benefits of simpler operation, elimination of the potentially dangerous pressurized H₂ tank, and control over purity and medical production standards.

[0039] As shown in Fig. 2, the parahydrogen production system 210 may include a micro H₂ generator 212, a cooling device 214, and a microreactor 216. For example, the micro H₂ generator 212 may produce parahydrogen locally based on a request, as a non-limiting example, from a connected MRI or nuclear magnetic resonance (NMR) system. The micro H₂ generator 212 may use any available methods for H₂ production. The micro H₂ generator 212 may produce continuous flow of H₂ gas meeting safety and medical grade purity controls. A method suitable for production at higher pressures may be desirable to support the subsequent cooling stage. Alternatively or additionally, the micro H₂ generator 212 may include a micropump to increase the pressure as well.

[0040] Conversion to parahydrogen requires cooling of the H₂ gas to low temperature in the range of 20K to 80K. Preferably, the temperature may need to be in the range of 20K to 40K. A cooling device 214 may be used to cool the H₂ gas. The cooling device 214 may achieve cooling through Joule-Thompson expansion cooling. For example, the cooling device 214 may include a two-stage cooling system such as a Joule-Thompson system using H₂ as the second stage coolant. Thus, the cooling device 214 directly produces cooled H₂ gas. Alternatively or additionally, external cooling methods for low temperature cooling may be used. Cooling the H₂ gas may be achieved using intermittent or micro continuous flow cooling technologies.

[0041] After the H₂ gas is cooled by the cooling device 214, hydrogen gas may be converted to parahydrogen in a microreactor 216. The microreactor 216 may greatly accelerate the conversion using high surface area catalysts. In one non-limiting example, the catalyst may comprise activated charcoal or Iron(III) oxide. This microreactor 216 exposes the H₂ gas to an appropriate catalyst on the sides or within channels through which the H₂ flows. After conversion, a warming stage may be used to make the H₂ gas reach a preset temperature for subsequent reactions. The preset temperature may be determined by the optimal temperature of the reaction, engineering considerations such as material tolerance and condensation, and the temperature desired for introduction in the MRI or NMR. For example, body temperature (310K) may be desirable for introduction in human studies.

[0042] Hyperpolarized MR relies on long relaxation time nuclei such as ¹³C. The ¹³C nuclei are not present in high abundance in nature. Thus, enriched version of the ¹³C substrate need to be produced. While enriched substrates may be produced off-site, local production has some advantages. Thus, the polarization delivery system 200 further includes a substrate production system 220 for local production of substrates.

[0043] The substrate production system 220 may include a chemical selector 222 to select medical grade ¹³C or ¹⁵N enriched molecules for use as input chemicals for the substrate production system 220. In some aspects, the input chemicals may include enriched versions of CO₂ or simple organic molecules. The input chemicals may be transferred from the chemical selector 222 to a substrate synthesizer 224, which converts input chemicals to the substrate. For example, the synthesizer 224 may synthesize more complex substrates from the input chemicals with a reduced cost. The substrate synthesizer 224 may help to control chemical purity, and enable flexible production of different hyperpolarized agents if needed. The substrate synthesizer 224 may use different synthesis methods depending on the desired hyperpolarized agent. The substrate synthesizer 224 provides a flexible system for local production of specific chemicals using microfluidic methods.

[0044] As shown in Fig. 2, the polarization delivery system 200 further includes a hyperpolarization and conversion system 230. The hyperpolarization and conversion system 230 includes a spin transfer device 232 and a filtering device 234. For example, the hyperpolarization and conversion system 230 may include a

spin transfer device 232 that receives parahydrogen from the parahydrogen production system 210 and substrate from the substrate production system 220.

[0045] The hyperpolarization and conversion system 230 is fundamental to PHIP and its improvement with microfluidic and microreactor methods. In the hyperpolarization and conversion system 230, spin order transfer may be performed using continuous flow inputs from systems 210 and 220. Since the products from systems 210 and 220 are not particularly short-lived, another embodiment of the present disclosure includes storing accumulating products from systems 210 and 220 for input into a more rapid and higher volume conversion system 230.

[0046] The spin transfer device 232 may increase the pressure of the parahydrogen with a miniature pump to increase efficiency of the spin transfer or hydrogenation reaction. The spin transfer device 232 may use a plurality of strategies for spin order transfer.

[0047] There are several examples for spin order transfer. Parahydrogen spin order transfer to produce a hyperpolarized agent may be achieved by double hydrogenation of a substrate or by spin transfer without forming hydrogen bonds. In some aspects, methods for parahydrogen spin order transfer without forming hydrogen bonds includes techniques such as signal amplification by reversible exchange (SABRE). Spin order transfer can be achieved using a dissolved liquid catalyst (known as a homogeneous catalyst) or using a solid catalyst (known as a heterogeneous catalyst) attached to the walls of a fluid channel or within a microreactor. In one non-limiting example, the dissolved liquid catalyst and the solid catalyst comprise a rhodium-based catalyst. RF decoupling or very low magnetic fields induced by shielding may be used to decrease the decay rate of spin order as the volume builds up. Transfer of spin order from protons to the ^{13}C or ^{15}N nuclei can then be performed with either magnetic field cycling, or radiofrequency (RF) field application. Both of these transfer methods may be implemented as a transient or as a continuous flow process where the time dependence is implemented through spatial dependence of RF and magnetic fields accompanied by a steady velocity of continuous flow.

[0048] The spin transfer device 232 may implement small scale spatial field variation with microstrip technology. The spin transfer device 232 may provide further modification to the hydrogenated molecule using methods such as those

reported for pyruvate, that is chemical cleaving of an intermediate to provide the final molecule. Using one or more of the methods outlined above, the spin transfer device 232 then outputs the hyperpolarized agent and unreacted reagents to a filtering device 234. The filtering device 234 filters out impurities, catalysts, and unreacted reagents to isolate the hyperpolarized agent. In some aspects, the filtering device 234 includes an ion-exchange filter or other microfluidic separation techniques. The filtering device 234 may use pH and osmolality matching, testing assays, etc. When no cleaving is required, the filtering device 234 may precede the spin transfer device 232.

[0049] Figs. 3A-3D illustrate several examples of flow charts for spin order transfer. Fig. 3A is an example flow chart setting forth steps of a first method 300A for producing hyperpolarized agents in accordance with the present disclosure. The hydrogenation uses an externally supplied homogeneous catalyst. No post hydrogenation chemical alteration of the hyperpolarized agent is required. In step 310, the hyperpolarization and conversion system 230 mixes inputs from the parahydrogen production system 210 and substrate from the substrate production system 220 into a hydrogenation microreactor. The hyperpolarization and conversion system 230 also receives homogeneous catalyst and RF decoupling in step 310. For example, the spin transfer device may receive a homogeneous catalyst from an external supply, such as an external storage vessel. The homogenous catalyst may promote spin order transfer by hydrogenating the substrate with parahydrogen to produce a hyperpolarized agent. In step 312, the hyperpolarization and conversion system 230 may further promote spin order by field cycling. In step 314, the hyperpolarization and conversion system 230 filters out catalyst, impurities, and unreacted reagents to isolate the hyperpolarized agent. In step 316, the hyperpolarization and conversion system 230 dilutes the hyperpolarized agent from step 314 and matches pH and osmolality according to the request, for example, from the MRI system or other system connected to the polarization delivery system. In step 318, the hyperpolarization and conversion system sends the hyperpolarized agent to the infusion system 240.

[0050] Fig. 3B is an example flow chart setting forth steps of a second method 300B for producing hyperpolarized agents in accordance with the present disclosure. Here, the hyperpolarization and conversion system 230 achieves hydrogenation using an internally fixed heterogeneous catalyst. Little or no catalyst need be filtered

out and no post hydrogenation chemical alteration of the hyperpolarized agent is required using this method. In step 320, the hyperpolarization and conversion system 230 mixes parahydrogen from the parahydrogen production system 210 and substrate from the substrate production system 220 into a hydrogenation microreactor. The heterogeneous catalyst may promote spin order transfer by hydrogenating the substrate with parahydrogen to produce a hyperpolarized agent. The hyperpolarization and conversion system 230 also employs RF decoupling in step 320. In step 322, the hyperpolarization and conversion system 230 converts spin order by field cycling. In step 324, the hyperpolarization and conversion system filters unreacted reagents, impurities, and residual catalyst to isolate the hyperpolarized agent. In step 326, the hyperpolarization and conversion system dilutes the hyperpolarized agent from step 324 and matches pH and osmolality according to the request. In step 328, the hyperpolarization and conversion system sends the hyperpolarized agent to the infusion system 240.

[0051] Fig. 3C is an example flow chart setting forth steps of a third method for producing hyperpolarized agents in accordance with the present disclosure. Here, the hyperpolarization and conversion system employs SABRE using an externally supplied homogeneous catalyst. No filtering out of the substrate or post SABRE chemical alteration of the agent is required. In step 330, the hyperpolarization and conversion system 230 mixes inputs from the parahydrogen production system 210 and substrate from the substrate production system 220 into a SABRE microreactor. Spin order may be transferred from the parahydrogen to the substrate to produce a hyperpolarized agent, where the rate of spin order transfer may be facilitated by the homogenous catalyst. The hyperpolarization and conversion system 230 also employs RF decoupling. In step 332, the hyperpolarization and conversion system 230 converts spin order by field cycling. In step 334, the hyperpolarization and conversion system 230 filters the catalyst, impurities, and unreacted reagents to isolate the hyperpolarized agent. In step 336, the hyperpolarization and conversion system 230 dilutes the hyperpolarized agent from step 334 and matches pH and osmolality according to the request. In step 338, the hyperpolarization and conversion system sends the hyperpolarized agent to the infusion system 240.

[0052] Fig. 3D is an example flow chart setting forth steps of a fourth method for producing hyperpolarized agents in accordance with the present disclosure.

Here, the hyperpolarization and conversion system 230 employs hydrogenation using an internally fixed heterogeneous catalyst. Little or no catalyst need be filtered out. Post hydrogenation chemical alteration of the hyperpolarized agent may be required. In step 340, the hyperpolarization and conversion system 230 mixes parahydrogen from the parahydrogen production system 210 and substrate from the substrate production system 220. The hyperpolarization and conversion system 230 also employs RF decoupling. The heterogeneous catalyst may promote spin order transfer by hydrogenating the substrate with the parahydrogen to produce a hyperpolarized agent. In step 342, the hyperpolarization and conversion system 230 converts spin order by field cycling. In step 344, the hyperpolarization and conversion system 230 may cleave unwanted bonds with NaOH. In step 346, the hyperpolarization and conversion system 230 filters unreacted reagents, impurities, and residual catalyst to isolate the hyperpolarized agent. In step 348, the hyperpolarization and conversion system 230 dilutes the hyperpolarized agent and matches pH and osmolality according to the request. In step 350, the hyperpolarization and conversion system 230 sends the hyperpolarized agent to the infusion system 240.

[0053] In the above examples, replacement of field cycling with RF pulse methods is feasible. All possible combinations of the basic elements are not shown. RF decoupling may or may not be necessary to lengthen the lifetime of the spin order and could potentially be replaced with performing the operations at very low field. Some of the post-hydrogenation elements, such as spin order conversion, filtering, and dilution may be placed in different orders. The cleaving of unwanted hydrogens, as in Fig. 3D, may need to be performed after spin order conversion.

[0054] The disclosed systems and methods for hyperpolarization have greater promise for efficient, safe, inexpensive, and widespread use of hyperpolarized MR tracers. This method is based on PHIP, which is more chemically complex but has shown similar polarization efficiency to DNP. Progress with PHIP has been slow, in part, because of very primitive technology and chemistry sophistication. For example, initially it was felt that metabolic agents of interest, such as pyruvate, could not be polarized by PHIP. Recently however, it was shown that choice of an appropriate substrate and quick chemical modification allows hyperpolarization of pyruvate and potentially many other interesting molecules.

[0055] Further, PHIP does not require very low temperatures or high magnetic

fields, so miniaturization, cost reduction, and widespread distribution is likely much more feasible than DNP. Still, the field is developing PHIP slowly, with simple batch production methods and without the benefit of state-of-the-art chemical synthesis methods. The hyperpolarized agents may be used as MR tracers for perfusion imaging.

[0056] The present disclosure has been described in terms of one or more embodiments, and it should be appreciated that many equivalents, alternatives, variations, and modifications, aside from those expressly stated, are possible and within the scope of the disclosure. For example, it is contemplated that the above-described techniques may be used for on-demand continuous-flow production of polarized substrate for MRI or NMR.

[0057] The polarization delivery system may be packaged in a compact, reconfigurable, and mobile system. It is noted that different stages may function more effectively at different temperatures and pressures from each other. For example, hydrogenation may function more effectively at pressures up to 100x atmospheric pressure and at temperatures as low as 0°C or as high as 100°C. Cooling or heating stages within or between these stages may be necessary to achieve these conditions.

CLAIMS**WE CLAIM:**

1. A polarization delivery system comprising:
a parahydrogen production system comprising a microreactor that processes hydrogen based on a request from a magnetic resonance imaging (MRI) or nuclear magnetic resonance (NMR) system; and
a hyperpolarization and conversion system comprising a spin transfer device that receives the processed hydrogen from the microreactor and transfers spin order from the processed hydrogen to a substrate.
2. The polarization delivery system of claim 1 wherein the parahydrogen production system further comprises a micro hydrogen generator.
3. The polarization delivery system of claim 2 wherein the parahydrogen production system further comprises a cooling device connected between the micro hydrogen generator and the microreactor.
4. The polarization delivery system of claim 3 wherein the cooling device comprises a two-stage cooling system using hydrogen as a coolant for a second stage.
5. The polarization delivery system of claim 4 wherein the microreactor exposes the hydrogen to high surface area catalysts.
6. The polarization delivery system of claim 5 wherein the microreactor further comprises a warming stage that makes the hydrogen reach a preset temperature for subsequent reactions.
7. The polarization delivery system of claim 1, further comprising:
a substrate production system connected to the spin transfer device, the substrate production system comprising a substrate synthesizer that converts input chemicals to the substrate.

8. The polarization delivery system of claim 1 wherein the spin transfer device receives a homogeneous catalyst from an external supply.

9. The polarization delivery system of claim 1 wherein the spin transfer device employs a heterogeneous catalyst fixed internally in the spin transfer device.

10. The polarization delivery system of claim 1 wherein the hyperpolarization and conversion system further comprises a filtering device configured to receive polarized substrate from the spin transfer device.

11. The polarization delivery system of claim 10 wherein the filtering device filters out impurities in the polarized substrate and outputs the polarized substrate to the MRI or NMR system.

12. A method for producing polarized hydrogen for use during a magnetic resonance imaging (MRI) or nuclear magnetic resonance (NMR) process, the method comprising:

generating, with a micro hydrogen generator in a polarization delivery system, hydrogen based on a request;

processing, with a microreactor in the polarization delivery system, the hydrogen into parahydrogen based on the request;

receiving, by a spin transfer device, processed hydrogen from the microreactor; and

transferring, with the spin transfer device, spin order from the processed hydrogen to a substrate.

13. The method of claim 12 further comprising:
cooling, by a cooling device connected between the micro hydrogen generator and the microreactor, the hydrogen to a first temperature range.

14. The method of claim 13 further comprising:
exposing, by the microreactor, the hydrogen to high surface area catalysts.

15. The method of claim 14 further comprising:
warming, by a warming stage, the hydrogen to a second temperature range for subsequent reactions.
16. The method of claim 12 further comprising:
converting, by a substrate synthesizer connected to the spin transfer device, input chemicals to the substrate.
17. The method of claim 12 further comprising:
receiving, by the spin transfer device, a homogeneous catalyst from an external supply.
18. The method of claim 12 further comprising:
receiving, by a filtering device, polarized substrate from the spin transfer device; and
filtering out impurities in the polarized substrate and output the polarized substrate for use in the MRI or NMR process.
19. A method for producing contrast agent, the method comprising:
generating, for use with a magnetic resonance imaging (MRI) or nuclear magnetic resonance (NMR) system performing an MRI or NMR process, a request based on a subject to be scanned in the MRI or NMR system during the MRI or NMR process;
generating, with a micro hydrogen generator in a polarization delivery system, hydrogen based on the request;
processing, with a microreactor in the polarization delivery system, the hydrogen into parahydrogen based on the request;
receiving, by a spin transfer device, processed hydrogen from the microreactor; and
transferring, with the spin transfer device, spin order from the processed hydrogen to produce the contrast agent to be injected to the subject.
20. The method of claim 19 further comprising:

receiving, by a filtering device, polarized substrate from the spin transfer device; and

filtering out impurities in the polarized substrate and output the polarized substrate as the contrast agent to be injected to the subject.

21. An imaging system comprising:

a magnetic resonance imaging (MRI) or nuclear magnetic resonance (NMR) system configured to perform an MRI or NMR process to acquire imaging data from a subject to be scanned in the MRI or NMR system during the MRI or NMR process;

a hyperpolarization system comprising a spin transfer device that receives hydrogen and transfers spin order from the hydrogen to a substrate; and

a computer system configured to:

develop a pulse sequence to carry out the MRI or NMR process;

generate a request for processed hydrogen to be received from the hyperpolarization system to carry out the MRI or NMR process;

carry out the MRI or NMR process using the pulse sequence to acquire the imaging data from the subject having received the processed hydrogen; and

reconstruct an image of the subject using the imaging data.

22. The imaging system of claim 21 further comprising a parahydrogen production system comprising a microreactor or microfluidic device that processes hydrogen based on the request from the MRI or NMR system.

23. The imaging system of claim 22 wherein the parahydrogen production system further comprises a micro hydrogen generator.

24. The imaging system of claim 23 wherein the parahydrogen production system further comprises a cooling device connected between the micro hydrogen generator and the microreactor or microfluidic device.

25. The imaging system of claim 24 wherein the microreactor or microfluidic device exposes the hydrogen to high surface area catalysts.

26. A microfluidic or microreactor polarization delivery system comprising:

a parahydrogen production system comprising a microfluidic or microreactor that processes hydrogen based on a request from a magnetic resonance imaging (MRI) or nuclear magnetic resonance (NMR) system; and

a hyperpolarization and conversion system comprising a spin transfer device that receives the processed hydrogen from the microfluidic or microreactor and transfers spin order from the processed hydrogen to a substrate.

27. The polarization delivery system of claim 26 wherein the parahydrogen production system further comprises a micro hydrogen generator.

28. The polarization delivery system of claim 27 wherein the parahydrogen production system further comprises a cooling device connected between the micro hydrogen generator and the microreactor or microfluidic device.

29. The polarization delivery system of claim 26 wherein the microreactor or microfluidic device exposes the hydrogen to high surface area catalysts.

30. The polarization delivery system of claim 29 wherein the microreactor further comprises a warming stage configured to warm the hydrogen to a preset temperature for subsequent reactions.

31. The polarization delivery system of claim 26, further comprising a microreactor or microfluidic substrate production system connected to the spin transfer device, the substrate production system comprising a substrate synthesizer that converts input chemicals into the substrate.

32. The polarization delivery system of claim 26, wherein spin order is transferred to the substrate in a microfluidic or microreactor device.

33. The polarization delivery system of claim 32, wherein the spin order transfer is achieved by hydrogenation of the substrate using a homogeneous catalyst received from an external supply.

34. The polarization delivery system of claim 32, wherein the spin order transfer is achieved by hydrogenation of the substrate using a homogeneous or heterogeneous catalyst that is fixed within the spin order transfer device.

35. The polarization delivery system of claim 32, wherein the spin order transfer is achieved by reversible exchange to the substrate using a homogeneous catalyst received from an external supply.

36. The polarization delivery system of claim 32, wherein the spin order transfer is achieved by reversible exchange to the substrate using a homogeneous or heterogeneous catalyst that is fixed within the spin order transfer device.

37. The polarization delivery system of claims 32, wherein the spin order transfer device is exposed to a magnetic field to maintain the spin order.

38. The polarization delivery system of claim 37, wherein the spin order transfer device is exposed to an electromagnetic decoupling field to maintain the spin order.

39. The polarization delivery system of claim 26 wherein one or more microfluidic or microreactor devices chemically transform, filter, dilute, or buffer the output of the spin order transfer device.

40. The polarization delivery system of claim 26 further comprising a microfluidic or microreactor device and wherein spin order is converted to magnetization of a non-hydrogen nucleus within the microfluidic or microreactor device by electromagnetic fields modulated by an external device or flow through spatially varying fields.

41. A method for parahydrogen production for imaging comprising:
processing hydrogen using a microfluidic or microreactor based on a request from a magnetic resonance imaging (MRI) or nuclear magnetic resonance (NMR) system; and

receiving the processed hydrogen from the microfluidic or microreactor and transferring spin order from the processed hydrogen to a substrate.

42. The method of claim 41 further comprising exposing the hydrogen to high surface area catalysts.

43. The method of claim 42 further comprising warming the hydrogen to a preset temperature for subsequent reactions.

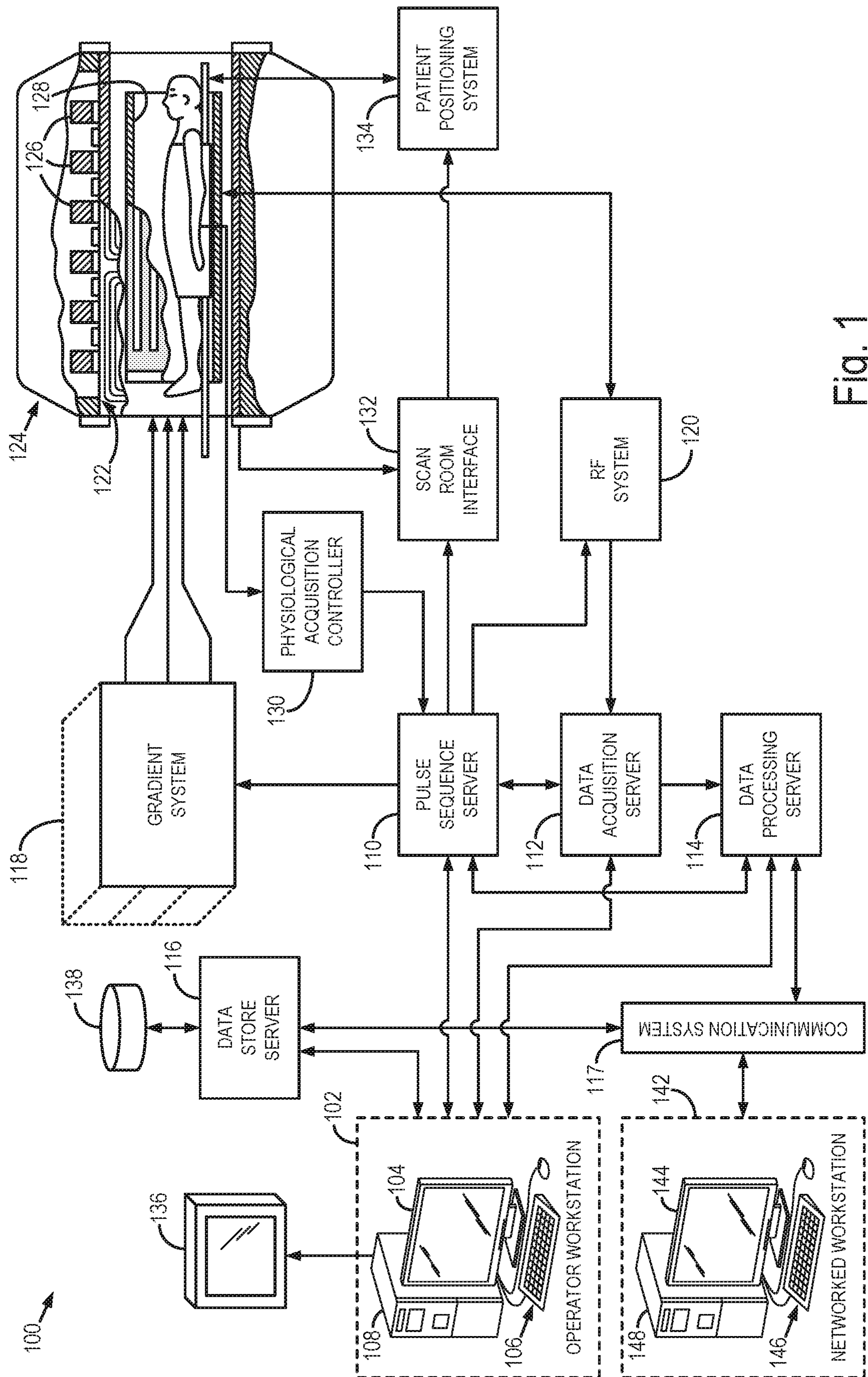
44. The method of claim 41 further comprising using a substrate synthesizer to convert input chemicals into the substrate.

45. The method of claim 41 wherein spin order is transferred to the substrate using the microfluidic or microreactor.

46. The method of claim 45 wherein transferring the spin order includes performing hydrogenation of the substrate using at least one of a homogeneous catalyst received from an external supply or a homogeneous or heterogeneous catalyst.

47. The method of claim 45 wherein transferring the spin order includes performing a reversible exchange to the substrate using at least one of a homogeneous catalyst received from an external supply or a homogeneous or heterogeneous catalyst.

48. The method of claims 41 further comprising using a magnetic field to maintain the spin order.



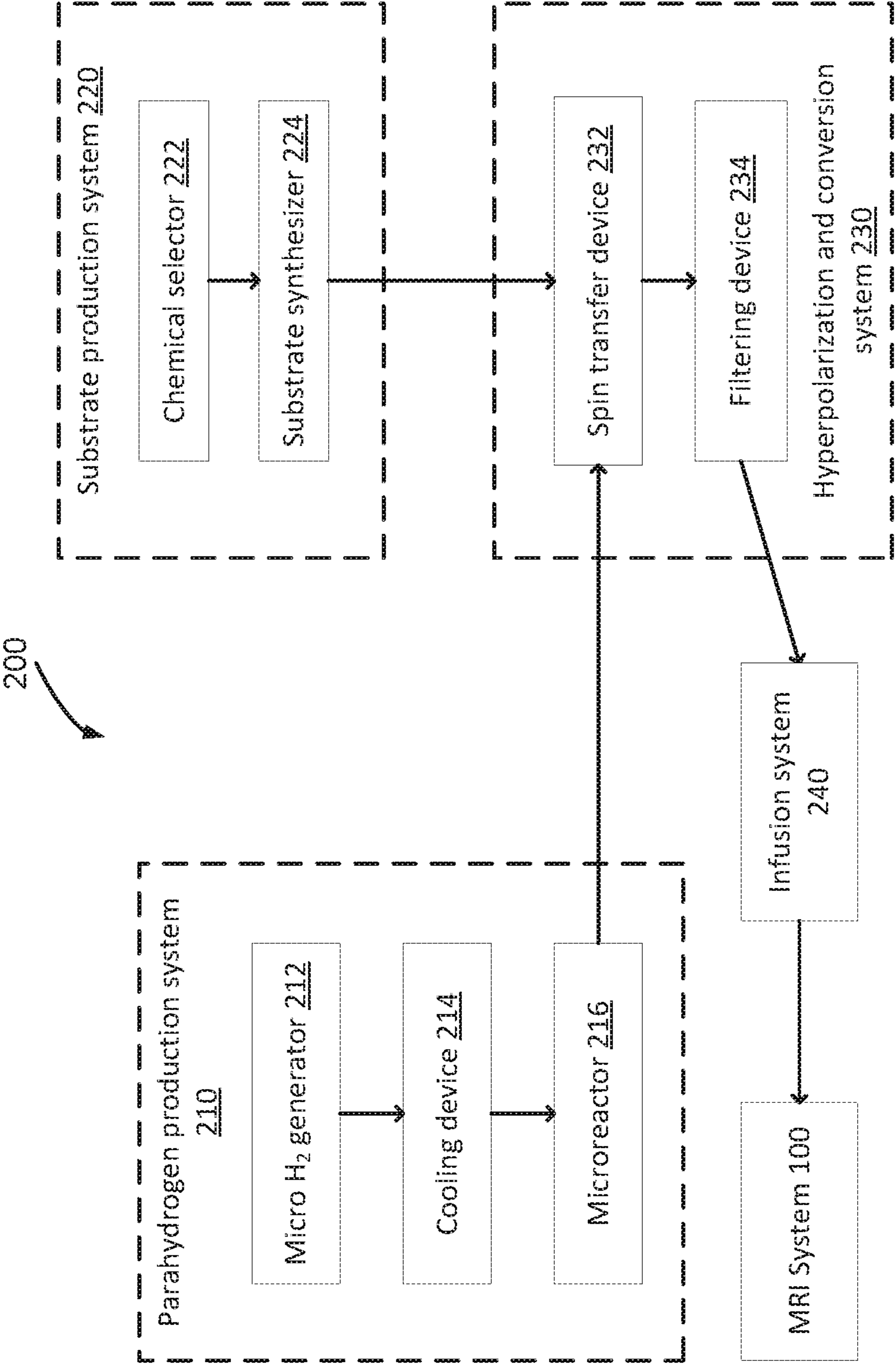


Fig. 2

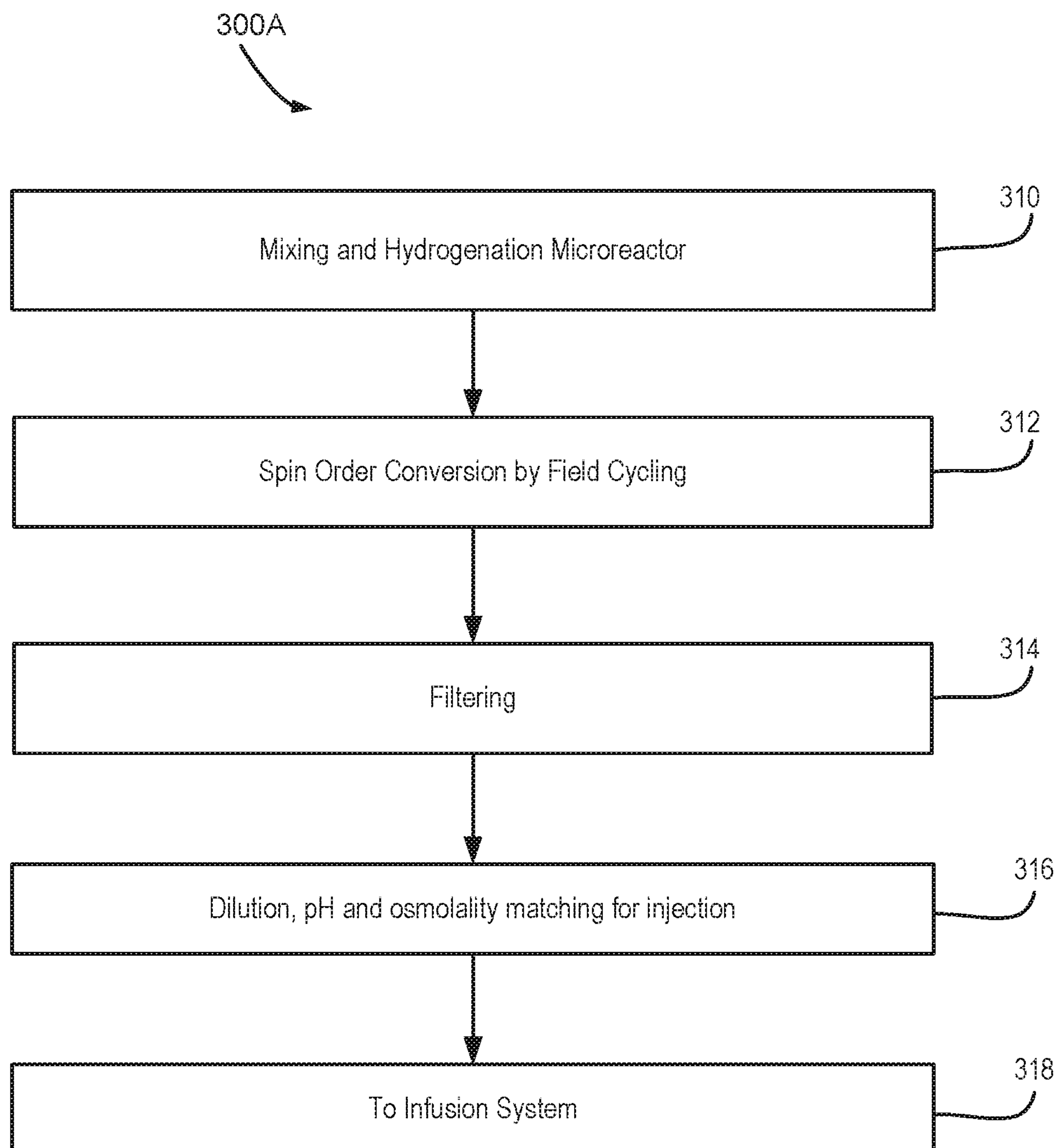


Fig. 3A

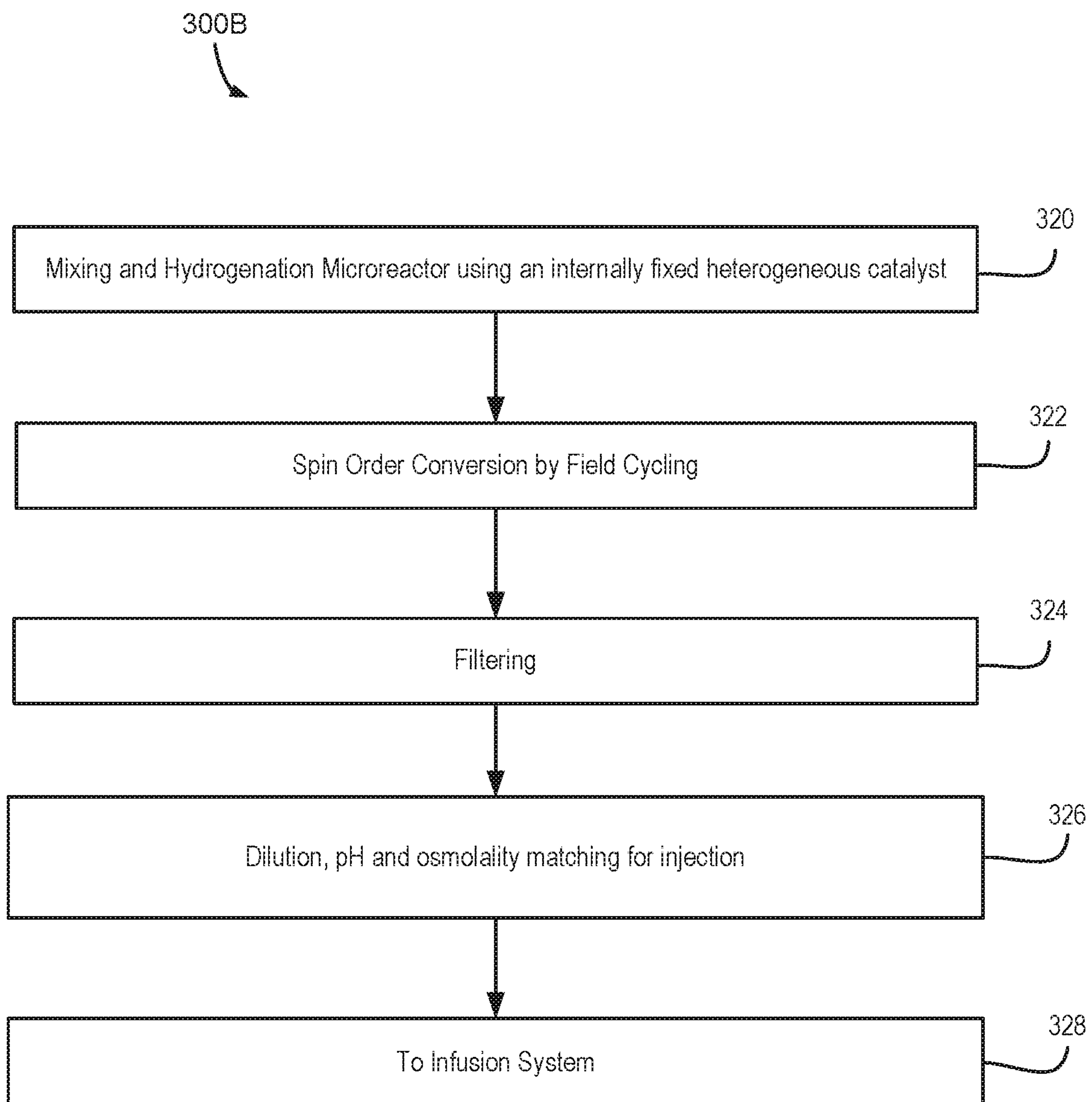


Fig. 3B

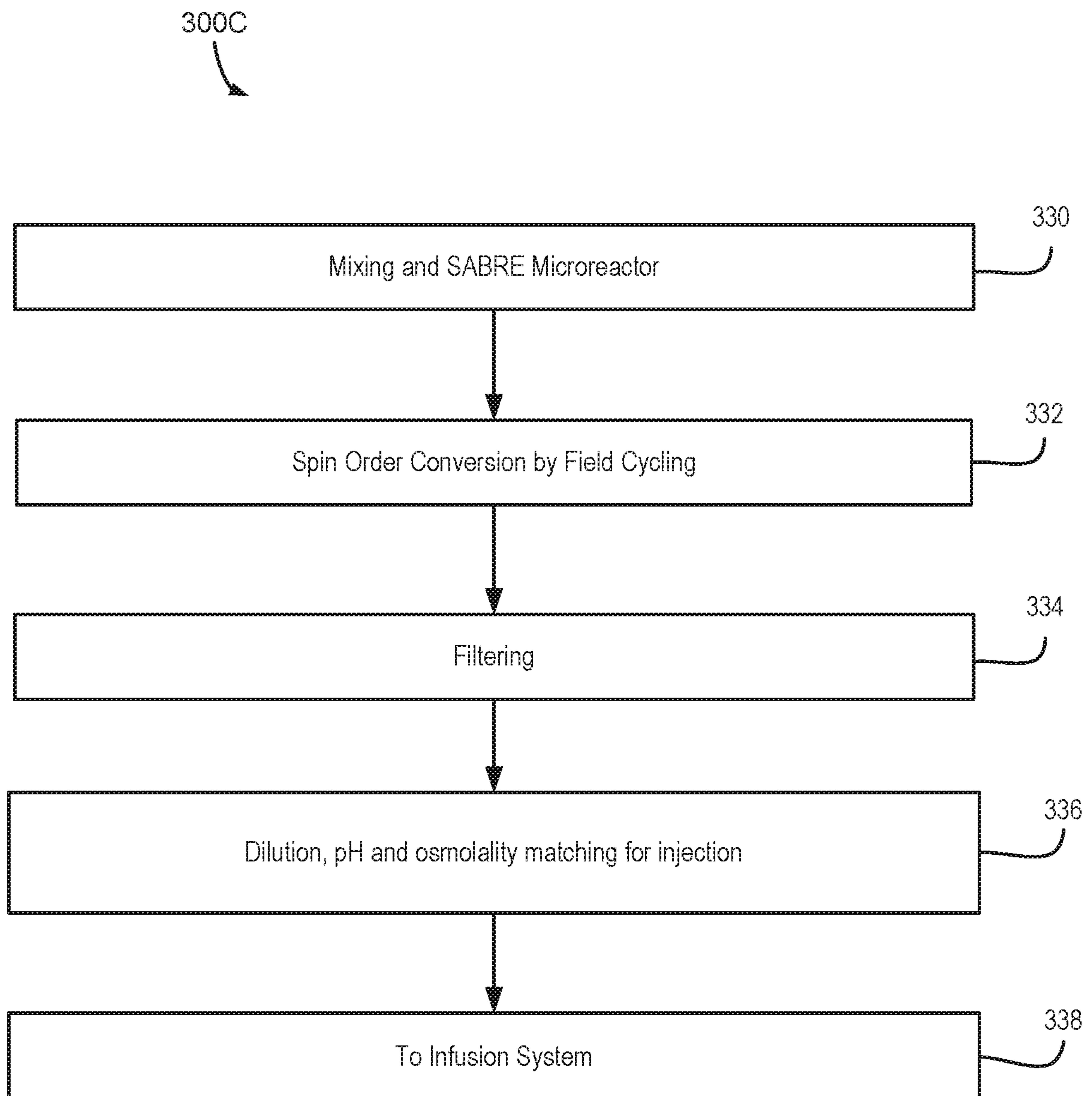


Fig. 3C

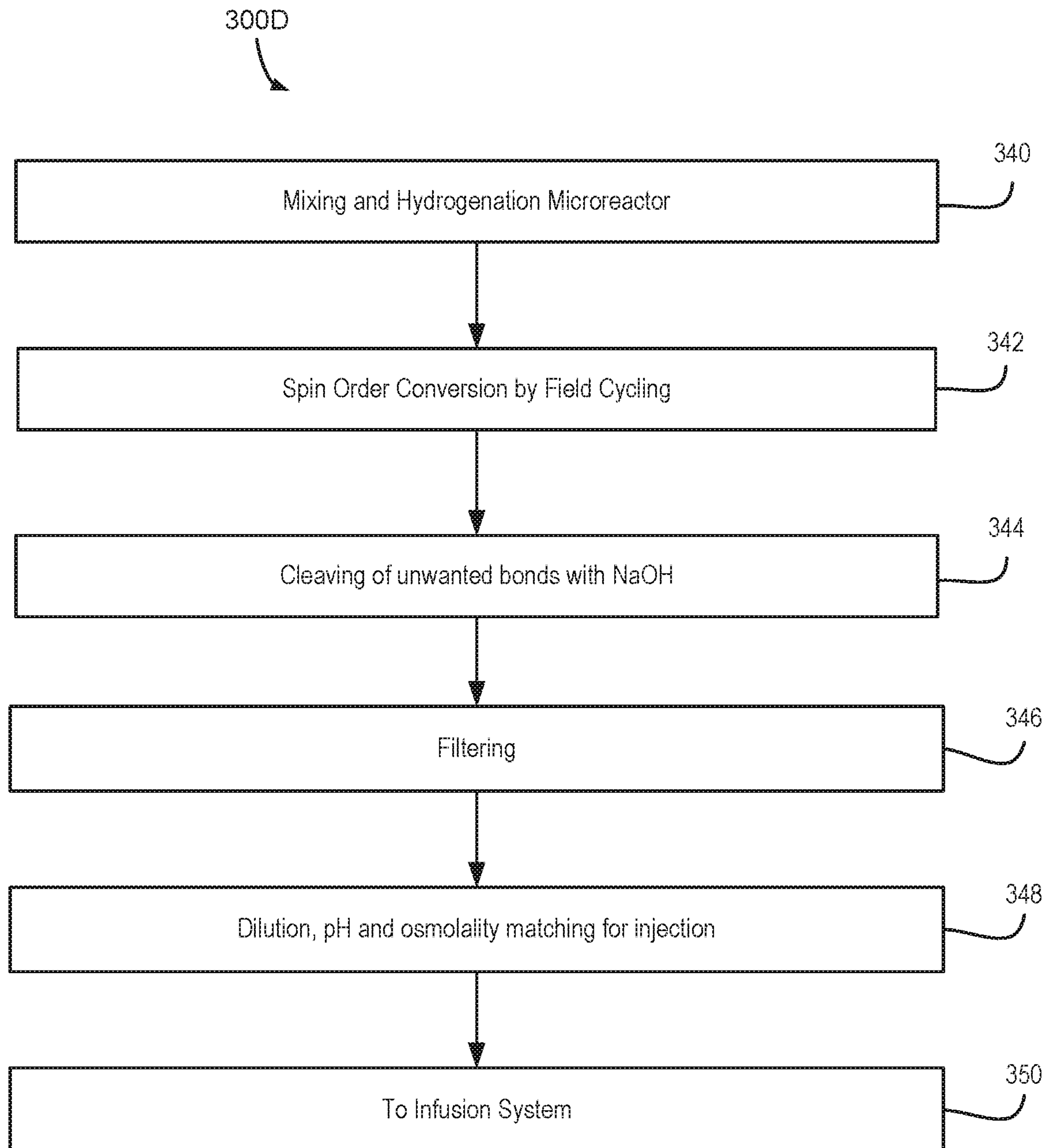


Fig. 3D

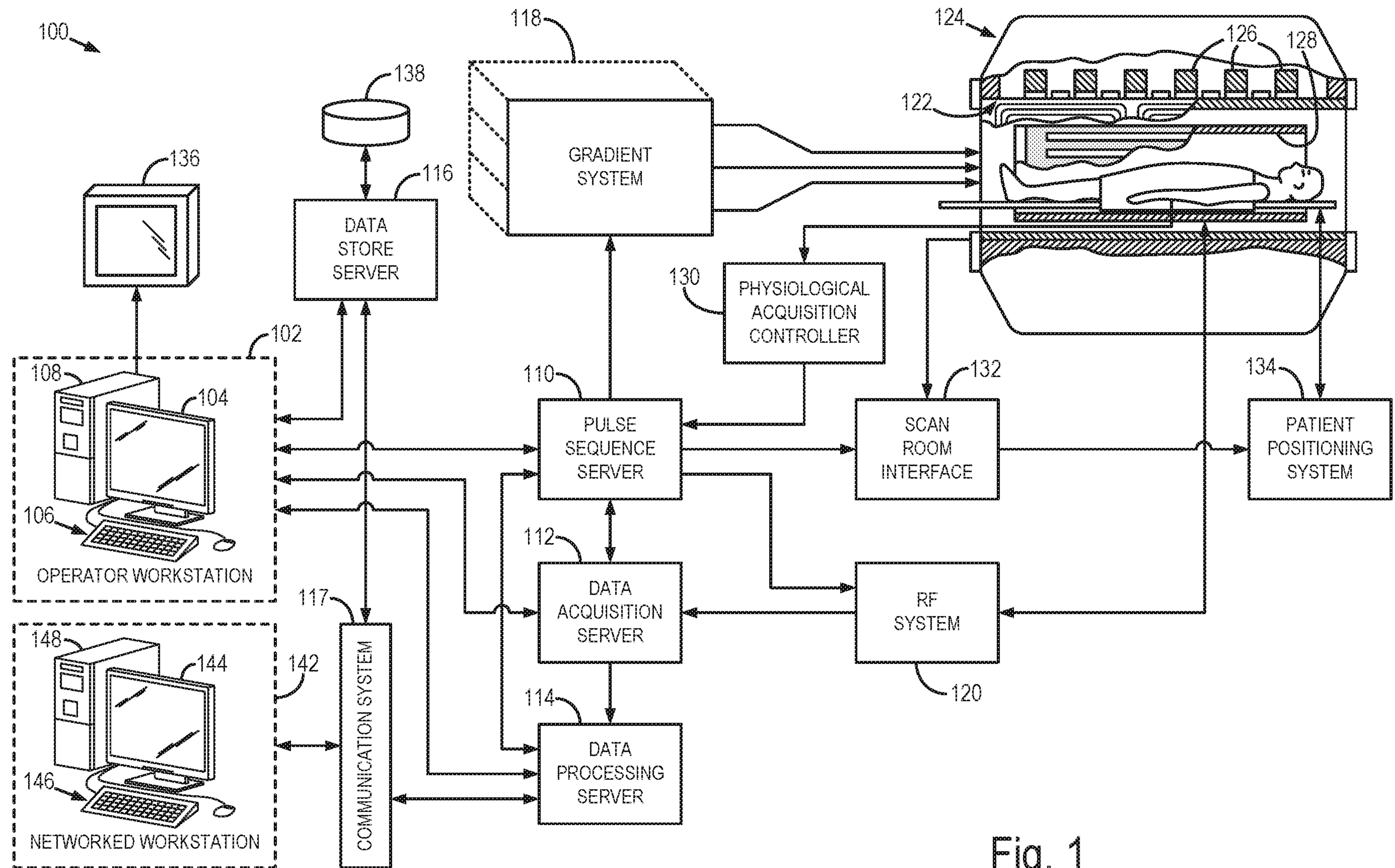


Fig. 1