

(RESEARCH ARTICLE)



QUANTUM MECHANICS OF MAGNETIC RESONANCE IMAGING TECHNOLOGIES: FROM NUCLEAR MAGNETIC RESONANCE TO DIAGNOSTIC IMAGE RECONSTRUCTION

Supreet Kaur *

Staff Biomedical Engineer, Wayne State University, Detroit, MI.

* Corresponding Author

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ABSTRACT

Magnetic resonance imaging (MRI) is a noninvasive medical-imaging modality founded on the combined principles of quantum mechanics, classical electromagnetism, and digital signal processing. Unlike X-ray- and computed-tomography-based modalities, MRI does not use ionizing radiation; instead, it detects radiofrequency signals generated by the collective behavior of nuclear magnetic moments within an applied magnetic field. Clinical MRI primarily uses hydrogen nuclei because they are abundant in biological water and lipids and have favorable magnetic properties. At the microscopic level, hydrogen protons possess intrinsic spins and associate magnetic spin moments. This article reviews the quantum principles and mathematical foundations that govern Magnetic resonance imaging aspects, including nuclear spin, the Zeeman Hamiltonian, Boltzmann population distributions, Larmor precession, Bloch-equation modeling, relaxation behavior, and pulse-sequence signal formation. It further evaluates how magnetic-field gradients spatially encode the MR signal through frequency and phase variation, how the acquired measurements populate k-space, and how inverse Fourier transformation reconstructs anatomical images. In addition, emerging quantum-enhanced approaches, including hyperpolarized MRI and diamond nitrogen-vacancy-center sensing technologies, are discussed as potential routes to improved signal sensitivity, molecular imaging, and advanced biomedical sensing technologies. This review connects microscopic quantum-spin behavior with the macroscopic engineering processes that enable modern diagnostic MRI imaging field.

Keywords: Magnetic resonance imaging (MRI); Quantum mechanics; nuclear spin; Zeeman splitting; Larmor frequency; Bloch equations; relaxation; K-space; Fourier reconstruction; Quantum sensing.

1 INTRODUCTION

Magnetic resonance imaging (MRI) is a major diagnostic and research technology because it provides excellent soft tissue contrast without exposing patients to ionizing radiation. MRI is based on nuclear magnetic resonance and primarily detects the behavior of hydrogen nuclei in water and lipids distributed throughout biological tissues [1,2,7–10].

The physical foundation of MRI is quantum mechanical in which the atomic nuclei with non-zero spin possess angular momentum and associated magnetic spin moments. When exposed to a strong static magnetic field, these nuclei occupy

discrete energy states and undergo resonant interaction with radiofrequency electromagnetic fields. The clinically detected MRI signal is the collective, macroscopic response of an immense ensemble of quantum spins. In a strong static magnetic field, these spins occupy discrete Zeeman energy states, creating a small thermal-equilibrium population imbalance that generates net longitudinal magnetization.

Radiofrequency excitation at the Larmor frequency perturbs this equilibrium and produces transverse magnetization that can be detected by receiver coils. The subsequent recovery of longitudinal magnetization and loss of transverse phase coherence are characterized by the relaxation constants T_1 , T_2 , and T_2^* , which provide the physical basis for tissue-dependent MRI contrast. Hydrogen is the principal nucleus used in routine MRI because it is highly abundant in the human body and has a relatively high gyromagnetic ratio. The hydrogen nucleus, consisting of one proton, behaves as a spin-1/2 system and provides the signal source for most diagnostic MR examinations [7–10].

Quantum computing and quantum machine learning are novel concepts that are now explored for medical-image reconstruction, classification, segmentation, and optimization, and demonstrated benefits remain problem-specific and are limited by present hardware noise, qubit capacity, data-encoding overhead, and the challenge of efficiently obtaining clinically useful classical output from quantum states.

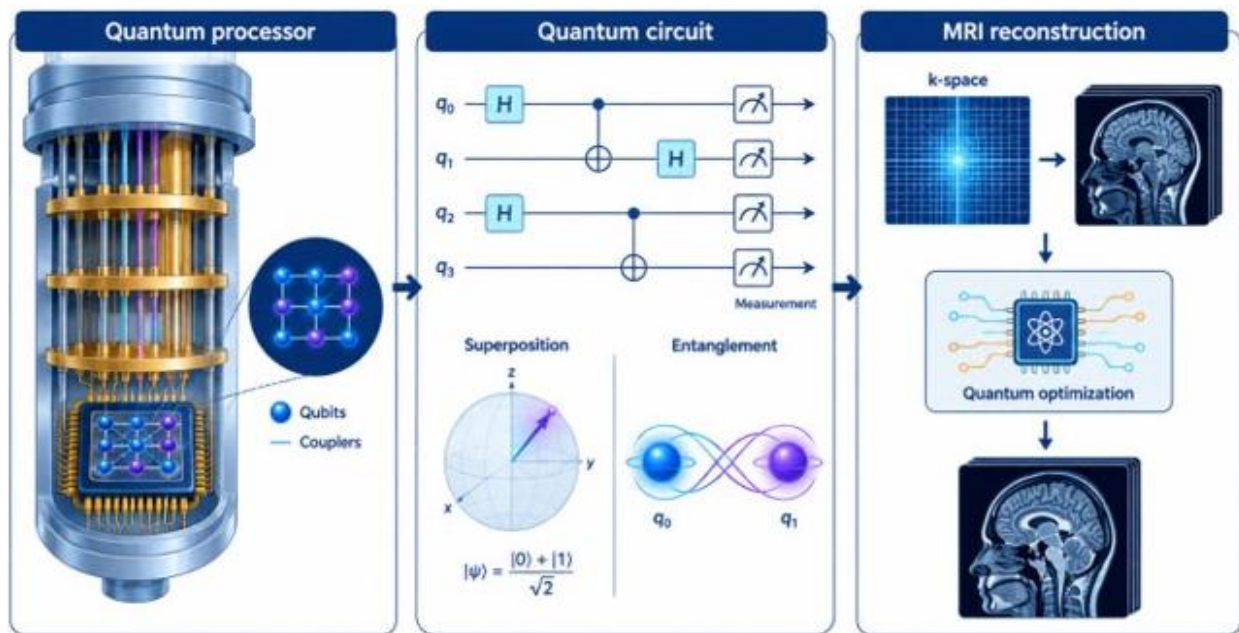


Figure 1: Conceptual quantum-computing workflow and its potential relevance to MRI reconstruction and optimization.

The figure illustrates a quantum processor containing coupled qubits, controlled through a quantum circuit. A qubit can be prepared in a superposition of the computational basis states, conventionally expressed as:

$$|\psi\rangle = \alpha |0\rangle + \beta |1\rangle, \text{ where } |\alpha|^2 + |\beta|^2 = 1.$$

In quantum computing, a qubit or a quantum bit is a basic unit of quantum information, a quantum version of classic binary unit. A qubit can be physically placed in a two-state quantum mechanical system. For example, the spin of electron in which the two levels can be taken as a spin up and spin down.

Quantum gates, including Hadamard and controlled-NOT gates, manipulate qubit states and generate entanglement; measurement converts the quantum state into a classical output. The right side presents a conceptual, not yet routine clinical, application to MRI: K-space data are supplied to a quantum or hybrid quantum–classical optimization workflow intended to support image reconstruction, feature extraction, sequence optimization, or image-analysis tasks.

2 QUANTUM MECHANICAL PRINCIPLES: BASIS OF MRI IMAGE RECONSTRUCTION

2.1 Nuclear spin and magnetic moment

The nuclear magnetic moment is proportional to the nuclear spin angular momentum:

$$\hat{\mu} = \gamma \hbar \hat{I}$$

where $\hat{\mu}$ is the magnetic-moment operator, γ is the gyromagnetic ratio, $\hbar$ is the reduced Planck constant, and $\hat{I}$ is the nuclear spin operator.

When the nucleus is placed in a static magnetic field B_0 , conventionally directed along the z-axis, its magnetic interaction is described by the Zeeman Hamiltonian:

$$\hat{H}_Z = -\hat{\mu} \cdot B_0$$

$$\text{For } B_0 = B_0 \hat{z}:$$

$$\hat{H}_Z = -\gamma \hbar B_0 \hat{I}_z$$

For a spin-1/2 proton, the permitted magnetic quantum numbers are:

$$m_I = +1/2, \quad m_I = -1/2$$

The corresponding energy values and energy separation are:

$$E(m_I) = -\gamma \hbar B_0 m_I$$

$$\Delta E = \hbar \gamma B_0$$

This Zeeman splitting is the quantum origin of MRI resonance. The static field determines the energy separation and thereby the required RF excitation frequency [7,8,13].

2.2 Thermal spin distribution

At thermal equilibrium, the relative populations of the two proton-spin states are described by the Boltzmann distribution:

$$N_{\text{high}} / N_{\text{low}} = \exp(-\Delta E / k_B T)$$

At physiological temperatures, ΔE is much smaller than thermal energy, and the relative population excess may be approximated as:

$$(N_{\text{low}} - N_{\text{high}}) / N_{\text{total}} \approx \hbar \gamma B_0 / (2k_B T)$$

Although the imbalance is small, the enormous number of hydrogen nuclei in the body creates a measurable net equilibrium magnetization M_0 .

3 LARMOR PRECESSION AND RF EXCITATION

The magnetic moment of a proton precesses around the main magnetic field at the Larmor angular frequency:

$$\omega_0 = \gamma B_0$$

The corresponding frequency in hertz is:

$$f_0 = \omega_0 / (2\pi) = (\gamma / (2\pi)) B_0$$

For hydrogen nuclei, $\gamma / (2\pi) \approx 42.58$ MHz/T. Thus, the proton resonance frequency is approximately 63.9 MHz at 1.5 T and 127.7 MHz at 3.0 T.

An MRI system applies a time-varying RF magnetic field B_1 with a frequency close to the Larmor frequency:

$$\omega_{RF} \approx \omega_0$$

Under this resonance condition, RF energy is transferred efficiently to the spin system. In the quantum description, this represents transitions between Zeeman energy states. In the macroscopic description, the RF pulse rotates the net magnetization vector away from the longitudinal axis and creates detectable transverse magnetization [7–10].

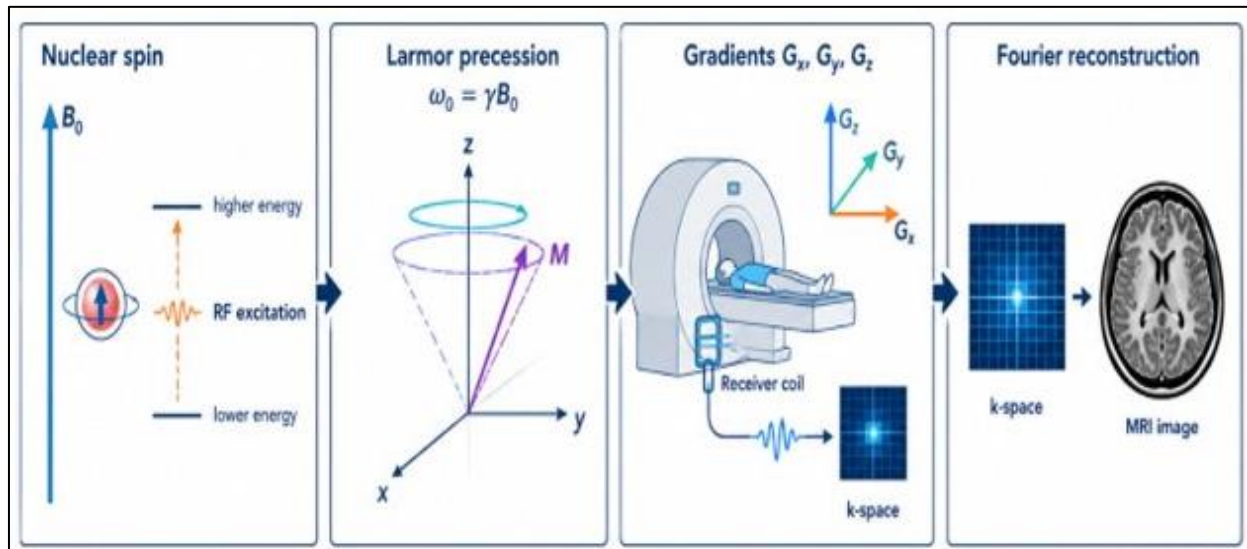


Figure 2: The schematic illustrates how hydrogen nuclear spin in the static magnetic field B_0 undergoes RF excitation and Larmor precession, after which gradient fields spatially encode the signal in k-space. Fourier reconstruction converts the acquired data into an MRI image.

Table 1 Summarizes Fundamental quantities and equations in MRI physics and nuclear magnetic moment, Zeeman Hamiltonian, energy splitting, Larmor frequency, and the hydrogen gyromagnetic ratio.

Table 1: Fundamental quantities and equations in MRI physics.

Quantity	Symbol / equation	Interpretation
Nuclear magnetic moment	$\hat{\mu} = \gamma \hbar \hat{I}$	Magnetic moment associated with nuclear spin.
Zeeman Hamiltonian	$\hat{H}_Z = -\hat{\mu} \cdot B_0$	Energy of a magnetic moment in the main field.
Energy splitting	$\Delta E = \hbar \gamma B_0$	Separation of proton spin energy states.
Larmor angular frequency	$\omega_0 = \gamma B_0$	Spin-precession rate in radians per second.
Larmor frequency	$f_0 = (\gamma/2\pi) B_0$	Spin-precession frequency in hertz.
Hydrogen gyromagnetic ratio	$\gamma/2\pi \approx 42.58 \text{ MHz/T}$	Relates proton resonance frequency to field strength.

Table 1. Summarizes Fundamental quantities and equations in MRI physics and nuclear magnetic moment, Zeeman Hamiltonian, energy splitting, Larmor frequency, and the hydrogen gyromagnetic ratio.

4 BLOCH EQUATIONS AND RELAXATION

The macroscopic magnetization of a proton ensemble is represented as:

$$\mathbf{M}(t) = [M_x(t), M_y(t), M_z(t)]^T$$

The Bloch equations describe its evolution in a magnetic field:

$$d\mathbf{M}/dt = \gamma \mathbf{M} \times \mathbf{B} - (M_x/T_2) \hat{x} - (M_y/T_2) \hat{y} - ((M_z - M_0)/T_1) \hat{z}$$

The precessional term $\gamma \mathbf{M} \times \mathbf{B}$ describes rotation of magnetization in the magnetic field. The remaining terms model longitudinal recovery and transverse decay. The Bloch equations are a macroscopic approximation to the collective behavior of quantum spins and form the principal engineering model used for MRI sequence design and signal prediction [1,3,9,30].

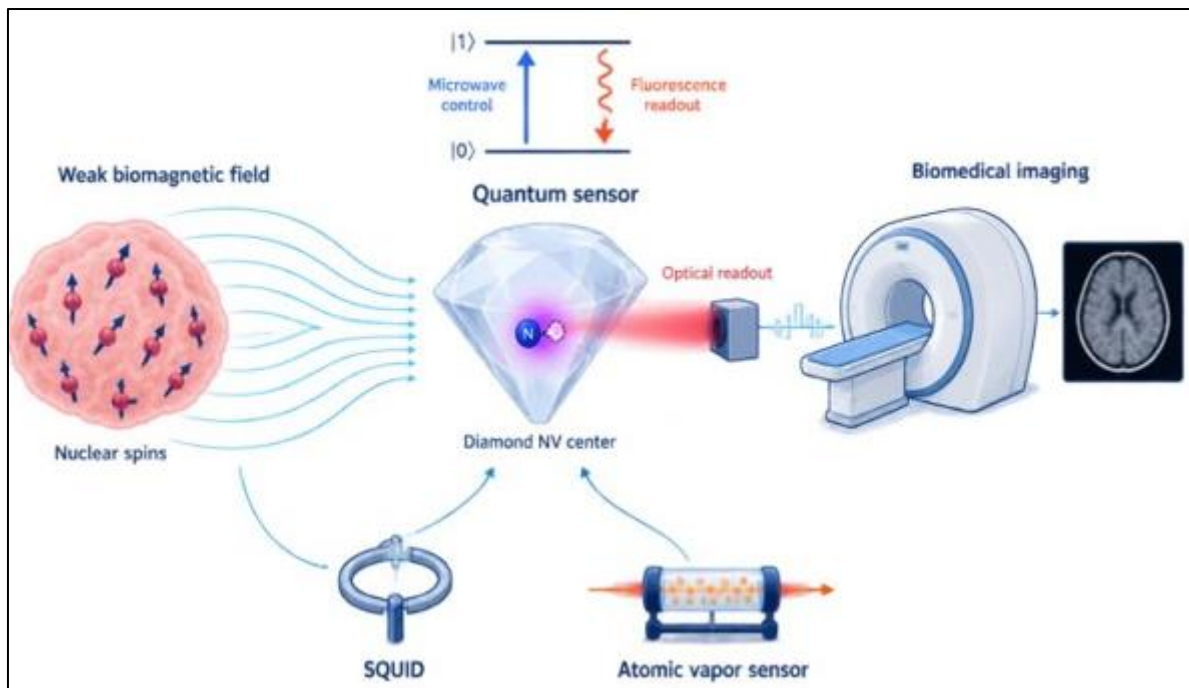


Figure 3: Quantum sensors for biomedical magnetic-field detection and MRI-related imaging.

Figure 3 illustrates a conceptual quantum-sensing workflow in which weak magnetic fields produced by nuclear spins in a biological sample are detected using a diamond nitrogen-vacancy (NV) center, a crystal defect comprising a substitutional nitrogen atom adjacent to a vacant carbon-lattice site. Diamond nitrogen-vacancy centers, superconducting devices, and other quantum-enabled magnetometers may enable highly sensitive detection of weak local magnetic fields. Potential long-term applications include microscale nuclear magnetic resonance, molecular characterization, nanoscale imaging, and integration with low-field or portable imaging systems.

Optical illumination initializes and reads out the NV electronic spin state through fluorescence, while microwave excitation probes magnetic-field-dependent transitions between its quantized energy levels. The schematic also presents superconducting quantum interference devices (SQUIDs) and atomic-vapor magnetometers as complementary quantum magnetic-sensing platforms. These technologies may support highly sensitive magnetic detection and future biomedical imaging applications; however, the depicted MRI connection is conceptual rather than a representation of routine clinical hardware.

4.1 Longitudinal relaxation

Longitudinal or spin-lattice relaxation is characterized by the time constant T_1 . After an ideal 90° RF excitation pulse:

$$M_z(t) = M_0(1 - e^{(-t/T_1)})$$

Tissues with short T_1 values recover longitudinal magnetization more rapidly than tissues with long T_1 values, producing T_1 -weighted contrast.

4.2 Transverse relaxation

Transverse or spin-spin relaxation is characterized by T_2 :

$$M_{xy}(t) = M_{xy}(0)e^{(-t/T_2)}$$

Additional dephasing caused by local field variation produces the effective relaxation constant T_2^* :

$$1/T_2^* = 1/T_2 + 1/T_2'$$

The shorter T_2^* value is important in gradient-echo imaging and susceptibility-sensitive sequences [9–12,21].

5 SIGNAL FORMATION AND IMAGE CONTRAST

A simplified spin-echo signal equation is:

$$S(TR, TE) \propto \rho (1 - e^{(-TR/T_1)})e^{(-TE/T_2)}$$

where S is MR signal intensity, ρ is proton density, TR is repetition time, and TE is echo time. A simplified gradient-echo relationship is:

$$S_{GRE} \propto \rho(1 - e^{(-TR/T_1)})e^{(-TE/T_2^*)}$$

A more complete steady-state spoiled gradient-echo approximation includes the excitation flip angle α :

$$S_{GRE} \propto \rho [(1 - e^{(-TR/T_1)})\sin \alpha] / [1 - e^{(-TR/T_1)}\cos \alpha] \cdot e^{(-TE/T_2^*)}$$

These equations allow engineers and MRI physicists to select timing parameters that create T_1 -weighted, T_2 -weighted, proton-density-weighted, or susceptibility-sensitive images [9–12,20].

6 SPATIAL ENCODING AND K-SPACE

MRI localizes signals by applying linear magnetic-field gradients along three spatial directions. The total magnetic field is:

$$B(r, t) = B_0 + G_x(t)x + G_y(t)y + G_z(t)z$$

The local Larmor angular frequency therefore becomes:

$$\omega(r, t) = \gamma[B_0 + G_x(t)x + G_y(t)y + G_z(t)z]$$

For an x-directed frequency-encoding gradient:

$$\Delta\omega(x) = \gamma G_x x$$

$$\Delta f(x) = (\gamma/(2\pi)) G_x x$$

The phase accumulated by spins at position r is:

$$\varphi(r, t) = \gamma \int_0^t G(\tau) \cdot r \, d\tau$$

The k-space coordinate is defined as:

$$k(t) = (\gamma/(2\pi)) \int_0^t G(\tau) d\tau$$

$$\varphi(r, t) = 2\pi k(t) \cdot r$$

K-space is the spatial-frequency domain in which MRI data are acquired. Its central region primarily influences broad image signal and contrast, whereas peripheral regions contain higher spatial-frequency information associated with fine structural detail and edge definition [4,5,17–19].

7 FOURIER IMAGE RECONSTRUCTION

The received MRI signal can be modeled as the Fourier transform of the transverse magnetization distribution:

$$s(k) = \int \rho(r) e^{(-i2\pi k \cdot r)} dr$$

For two-dimensional imaging:

$$s(k_x, k_y) = \iint \rho(x, y) e^{(-i2\pi(k_x x + k_y y))} dx dy$$

The image is reconstructed by inverse Fourier transformation:

$$\rho(r) = \int s(k) e^{i2\pi k \cdot r} dk$$

In practice, k-space is sampled discretely and reconstructed using a discrete Fourier transform or fast Fourier transform algorithm. MRI is therefore a computational reconstruction of spatially encoded nuclear magnetic resonance signals rather than a direct photograph of anatomy [17–19].

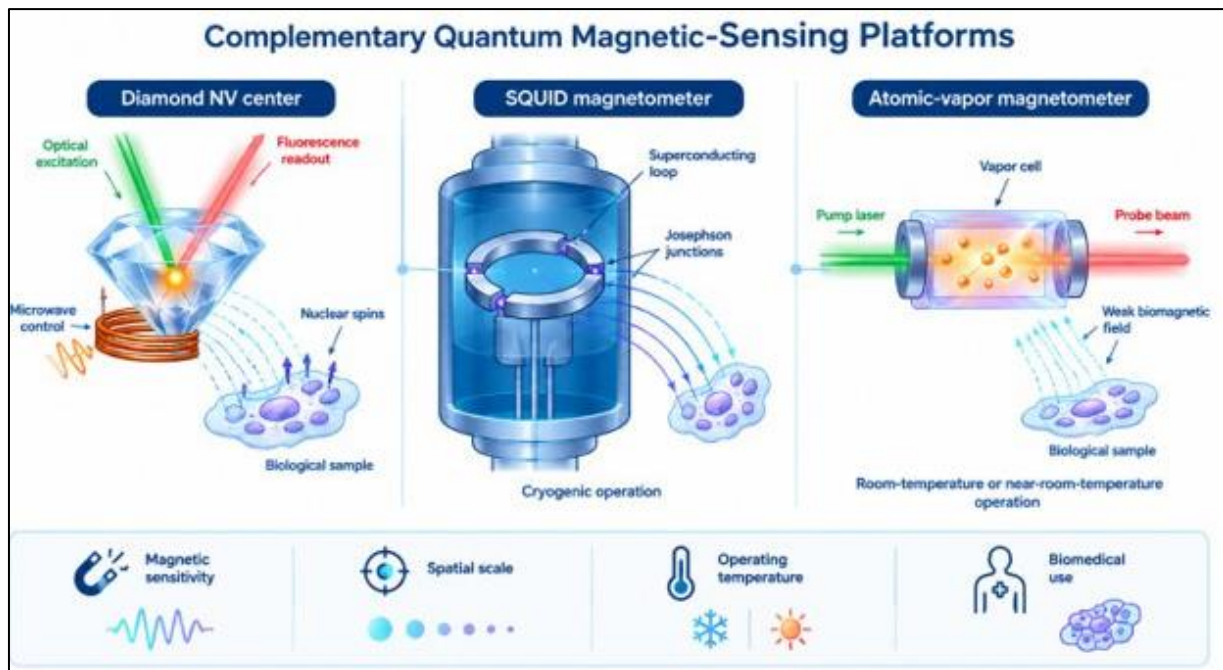


Figure 4: Comparison between three new complementary quantum magnetic-sensing platforms technologies for detecting extremely weak magnetic fields: Diamond nitrogen-vacancy (NV) centers, Superconducting quantum interference devices (SQUIDs), and optically pumped atomic-vapor magnetometers. All three are quantum-enabled sensing technologies, but they use different physical systems, readout methods, operating conditions, and potential biomedical applications.

The left panel shows a diamond containing a **nitrogen-vacancy center**: a defect in the carbon crystal lattice formed by a nitrogen atom adjacent to a missing carbon atom as shown in Figure 4. The NV center has an electron spin whose quantum energy levels change in response to an external magnetic field.

- Green light optically initializes the NV spin state.
- Microwave control probes transitions between its spin energy levels.
- Red fluorescence is collected as the optical readout signal.
- Magnetic fields from nearby nuclear spins or biological magnetic sources shift the NV-center resonance frequencies, allowing local field measurement.

NV centers are attractive because they can operate over a wide temperature range, can be physically robust, and can achieve very fine spatial resolution when positioned close to a sample. Their main potential is localized magnetic imaging, nanoscale or microscale nuclear magnetic resonance, and sensing near cells, tissues, magnetic nanoparticles, or molecular systems—not replacement of a whole-body clinical MRI scanner.

The middle panel depicts a SQUID magnetometer. A SQUID contains a superconducting loop interrupted by one or more **Josephson junctions**. Magnetic flux passing through the loop changes the electrical behavior of the superconducting circuit, enabling exceptionally sensitive magnetic-field measurement. The figure places the SQUID inside a cryogenic dewar because conventional SQUID systems require cooling to maintain superconductivity. This operating requirement is a key distinction from NV-center and atomic-vapor sensors. SQUIDs have historically been important for biomagnetic measurements, especially magnetoencephalography (MEG) and magnetocardiography. Their high sensitivity is valuable for detecting weak magnetic fields produced by neural or cardiac electrical activity, but the required cryogenic system can make instrumentation bulky, costly, and less flexible for patient placement.

The right panel shows an optically pumped atomic-vapor magnetometer, often using an alkali-metal vapor in a small, sealed cell. Laser light prepares, or “pumps,” the atomic spins into a known quantum state. A second optical beam probes changes in the atoms’ spin orientation or optical properties caused by an external magnetic field.

- The **pump laser** aligns atomic spins.
- The weak biomagnetic field changes their precession or energy-state behavior.
- The **probe beam** detects the resulting optical change.
- The measured optical signal is converted into magnetic-field information.

Atomic-vapor magnetometers can offer high sensitivity without cryogenic cooling. They are increasingly explored as wearable or flexible alternatives to SQUID-based MEG, since sensors can be positioned closer to the head and can accommodate some patient movement more readily than fixed helmet-based cryogenic systems.

8 QUANTUM-ENHANCED MRI AND IMAGING TECHNOLOGIES

Conventional clinical MRI already relies on quantum nuclear-spin behavior. Advanced quantum technologies may further improve MR sensitivity, molecular specificity, or magnetic-field detection. Hyperpolarization increases the population difference between spin states beyond the small thermal-equilibrium value. This substantially increases MRI signal and enables imaging of low-concentration nuclei and metabolic processes. Hyperpolarized carbon-13 compounds, particularly $[1-^{13}\text{C}]$ pyruvate, have been used to investigate metabolic activity in cancer and other diseases [24,25].

Diamond nitrogen-vacancy centers are emerging quantum-sensing platforms as shown in Figure 5. These point defects in diamond have quantum states that are sensitive to magnetic fields and could potentially detect extremely weak magnetic signals at small spatial scales. Such techniques are not routine in clinical MRI but are important directions for quantum-enabled biomedical imaging [26,27].

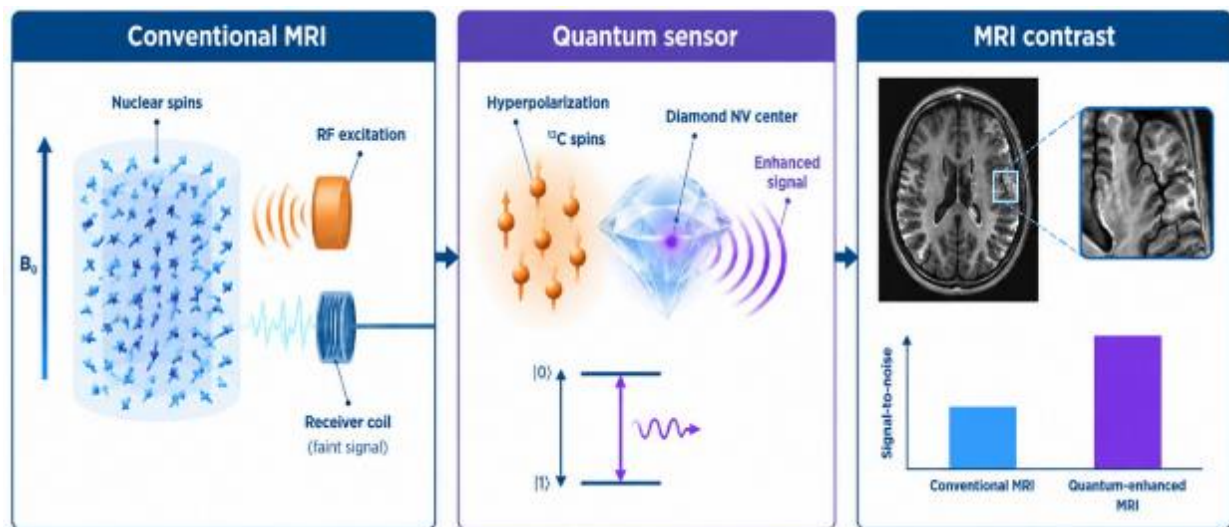


Figure 5: Conceptual comparison of conventional MRI signal detection and quantum-enhanced sensing. Conventional MRI measures weak nuclear-spin signals following RF excitation. Quantum-enhancement strategies, including hyperpolarization and diamond nitrogen-vacancy sensors, seek to increase sensitivity or enable detection of weak magnetic signals. This figure is conceptual and does not depict quantitative clinical performance.

9 DISCUSSION

MRI is a highly successful example of quantum physics translated into practical engineering and healthcare technology. Nuclear spin, magnetic moments, Zeeman splitting, and resonant RF excitation provide the microscopic quantum basis of the technique. The Bloch equations describe the macroscopic behavior of the spin ensemble, allowing prediction and control of magnetization evolution during pulse sequences.

Relaxation processes generate clinically valuable contrast because tissues differ in proton density, molecular motion, microscopic magnetic environment, and water content. Gradient fields encode location into frequency and phase, while k-space acquisition and inverse Fourier transformation produce the final image.

Diffusion-weighted MRI extends these principles to sensitivity to microscopic water motion and is particularly useful in acute ischemic stroke imaging. Blood-oxygen-level-dependent functional MRI uses T_2^* -sensitive contrast related to

changes in deoxyhemoglobin concentration, allowing indirect mapping of hemodynamic responses associated with neural activity [21–23].

Emerging approaches in hyperpolarization and quantum sensing may expand MRI beyond conventional anatomy and relaxation contrast. Their widespread clinical translation will depend on technical reliability, scanner compatibility, cost, safety, reproducibility, and demonstrated clinical value [24–27].

9.1 Conclusion & Future Directions

Magnetic resonance imaging is fundamentally a quantum-mechanical imaging technology. The energy levels of nuclear spins in a static magnetic field create the resonance condition for RF excitation. The net magnetization of a spin ensemble evolves according to the Bloch equations, relaxes according to tissue-dependent T_1 , T_2 , and T_2^* processes, and produces a measurable RF signal.

Magnetic-field gradients spatially encode this signal, and Fourier reconstruction converts sampled k-space data into an image. The full conceptual pathway is:

$$\hat{H}_Z \rightarrow \Delta E = \hbar \gamma B_0 \rightarrow \omega_0 = \gamma B_0 \rightarrow M(t) \rightarrow s(k) \rightarrow \rho(r)$$

Table 2: Comparison of the conventional clinical proton MRI with hyperpolarized MRI and diamond NV-center sensing imaging technology.

Key Aspect	Conventional clinical proton MRI	Hyperpolarized MRI	Diamond NV-center quantum sensing
Basic principle	A small equilibrium population imbalance of hydrogen spin states produces detectable net magnetization. Endogenous hydrogen in water and fat	External hyperpolarization creates a much larger spin-state population imbalance before measurement. Injected or administered hyperpolarized nuclei and their downstream metabolic products	Magnetic fields shift NV-center spin energy levels, which are read through optical fluorescence. Optical signal from the diamond sensor, modulated by the local magnetic field
Magnetic-field detection	RF receiver coils detect collective transverse nuclear magnetization	Multinuclear RF coils detect enhanced MR signals from hyperpolarized nuclei	Optical excitation, microwave control, and fluorescence readout detect NV spin-state changes
Primary information obtained	Anatomy, morphology, proton density, tissue relaxation, diffusion, perfusion, and selected functional contrast	Real-time metabolic flux, substrate-to-product conversion, molecular pathways, and tissue biochemistry	Local magnetic-field strength, direction, and spatial variation near the sensor
Typical MRI nucleus & Primary quantum system	Thermally polarized hydrogen (^1H) nuclear spins	Non-equilibrium polarized nuclei, commonly (^{13}C -labeled metabolic probes. Most commonly (^{13}C ; other nuclei may also be used	NV electron spin is the sensing element; nearby nuclear spins may be the magnetic-field source. Electron spin associated with a nitrogen-vacancy defect in a diamond lattice
Clinical use	Established routine diagnostic modality.	Emerging clinical and translational technology; actively investigated in oncology, cardiology, neurology, and metabolic disease.	Primarily laboratory, preclinical, and technology-development research; not part of routine clinical MRI.
Major limitation	Relatively low intrinsic spin polarization; acquisition time, motion, artifacts, and scanner cost can limit performance. Mature, standardized clinical technology.	Polarization is temporary; requires specialized polarizers, tracer preparation, rapid delivery, dedicated RF hardware, optimized sequences, and standardized protocols. Translational; early	Limited sensitivity at clinically relevant depth, restricted field of view, challenges with scanner integration, and incomplete clinical validation.

		clinical adoption at specialized centers.	Early-stage quantum-sensing research and preclinical development.
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The comparison distinguishes the conventional MRI, Hyperpolarized MRI and Diamond NV-center quantum sensing technologies as shown in Table 2.

Hyperpolarized MRI and NV-center sensing should be viewed as complementary rather than directly interchangeable technologies. Hyperpolarized MRI extends magnetic resonance toward real-time metabolic and molecular imaging at the organ level, whereas NV-center sensors focus on highly localized magnetic-field detection. Their future clinical value will depend on overcoming constraints related to polarization lifetime, acquisition hardware, depth sensitivity, reproducibility, standardization, and demonstrated benefit in patient care.

This progression connects quantum nuclear-spin physics to the engineering framework used to generate diagnostic MRI images. Future MRI development will likely combine advances in quantum physics, engineering hardware, acquisition strategies, computational reconstruction, and molecular imaging. One major direction is the wider translation of hyperpolarized MRI. Hyperpolarized carbon-13 agents can provide real-time information about metabolism rather than anatomy alone, potentially supporting earlier characterization of cancer, treatment response, cardiac metabolism, and inflammatory processes. Progress will depend on more reliable and cost-effective polarizers, transportable hyperpolarized probes, standardized acquisition and processing protocols, improved coil technology, and multicenter clinical validation.

A second direction is the development of quantum sensors for biomedical magnetic detection. Diamond nitrogen-vacancy centers, superconducting devices, and other quantum-enabled magnetometers may enable highly sensitive detection of weak local magnetic fields. Potential long-term applications include microscale nuclear magnetic resonance, molecular characterization, nanoscale imaging, and integration with low-field or portable imaging systems. Substantial engineering development is still needed to adapt these technologies for biologically relevant imaging depths, large fields of view, clinically practical scan times, and reliable operation in healthcare settings.

Improved MRI hardware will remain important. Higher-performance gradients, multichannel RF coils, parallel transmission, high-temperature superconducting components, and real-time RF safety monitoring may improve image quality while managing the safety and nonuniformity challenges associated with high-field and ultra-high-field MRI. In parallel, low-field and portable MRI platforms may improve accessibility in emergencies, intensive care, bedside, rural, and resource-limited settings. Their lower intrinsic signal can be partly addressed by optimized pulse sequences, improved detector technology, parallel imaging, compressed sensing, and learning-based reconstruction.

Computational MRI is also expected to play a central role. Physics-informed reconstruction, compressed sensing, parallel imaging, and artificial-intelligence-assisted image reconstruction can reduce scan time, improve signal-to-noise ratio, correct artifacts, and enable higher-resolution imaging from undersampled k-space data. Future methods should be evaluated carefully for robustness, reproducibility, bias, generalizability across scanners and patient populations, and clinical impact—not simply image appearance.

Finally, an important research objective is to build multiscale models that connect quantum spin behavior with tissue microstructure, molecular composition, physiological processes, and clinical outcomes. Such models could support quantitative MRI biomarkers, personalized acquisition protocols, more interpretable image reconstruction, and improved integration of MRI with metabolic, functional, and molecular imaging. Together, these developments may shift MRI from primarily structural imaging toward a more sensitive, quantitative, and biologically informative platform.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The author declares no conflict of interest.

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