Review Article

# A New Dimension in Imaging: The Rise of Synthetic MRI

*Radhika, Gulshan Kumar, Vishwanath Pratap Singh*

1. **MSc. RIT scholar**
2. **Assistant Professor**
**Department of Medical Radiology and Imaging Technology, Allied and Healthcare Sciences, Swami Vivekanand Subharti University Meerut (U.P)**

**Abstract:** Magnetic Resonance Imaging (MRI) is a cornerstone of modern medical diagnostics, known for its detailed imaging capabilities without the use of ionizing radiation. Traditional MRI requires multiple sequences to generate various contrast-weighted images such as T1-weighted, T2-weighted, and proton density images, which can be time-consuming and resource-intensive. Synthetic MRI introduces an innovative solution by synthesizing these images from a single acquisition using quantitative maps of tissue properties, including T1 and T2 relaxation times and proton density. This approach not only reduces scan times but also minimizes operation costs and improves patient comfort by consolidating imaging into a single scan. Synthetic MRI provides flexibility in post-acquisition image synthesis, facilitates quantitative tissue analysis, and enhances diagnostic precision with standardized and reproducible data. It has shown immense potential across various applications, including neurological imaging for diseases like multiple sclerosis and epilepsy, musculoskeletal evaluations for conditions such as osteoarthritis and soft tissue injuries, and oncological imaging for tumor characterization. Pediatric imaging benefits particularly from the reduced need for sedation due to shorter scan times, while cardiovascular and research applications continue to expand. However, challenges such as ensuring high-quality quantitative maps, integrating synthetic MRI into routine workflows, and replacing conventional sequences to avoid prolonged total scan times need to be addressed. Ongoing research aims to refine synthetic MRI, optimize image synthesis, and expand its clinical utility, paving the way for broader adoption in radiology.

**Keywords:** MRI, Epilepsy, Fingerprinting, Proton Density

**Abbreviations Used:** R1 – longitudinal relaxation rate, R2 – effective transverse relaxation rate, PD – proton density, TE – echo time, TR – repetition time, TI – inversion time, R1 – longitudinal relaxation rate, R2 – transverse relaxation time, T1w – T1 weighted, T2w – T2 weighted, MTLE - mesial temporal lobe epilepsy, HS - hippocampal sclerosis, MRF - magnetic resonance fingerprinting.

**Address for Correspondence:** Mr. Gulshan Kumar, M.Sc. RIT, Subharti College of Allied and Healthcare, The Faculty of Allied Health Sciences, Swami Vivekanand Subharti University, NH-58, Delhi-Haridwar Bypass Road, Meerut, Uttar Pradesh- 250005

**Email: gulshankumar3805@gmail.com** **Contact: +91-70183-56263**

**INTRODUCTION** - Magnetic Resonance Imaging (MRI) is a cornerstone in modern medical imaging, providing detailed images of the human body's internal structures without ionizing radiation. Traditional MRI relies on multiple sequences to generate various contrast images, which can be time-consuming and resource-intensive(1). Synthetic MRI, an innovative advancement, addresses these challenges by generating multiple contrast-weighted images from a single acquisition, offering significant efficiency and diagnostic capability advantages. Traditional MRI, which requires separate acquisitions for each type of image (T1-weighted (T2w), T2-weighted (T1w), and proton density), while synthetic MRI calculates these images based on quantitative maps of tissue properties such as T1 relaxation time, T2 relaxation time, and proton density. These quantitative maps are obtained from a single multi-parametric scan, which can then be used to synthesize any desired image contrast.[1] Synthesizing medical images can maximize the utility of acquired images and reduce scanner time and operation costs (radiotracers). Consequently, medical image synthesis has gained significant traction in clinical applications such as MRI only radiation therapy treatment planning, PET/MRI scanning, image segmentation, and image super-resolution.[2] Synthetic MRI is valuable because it synthesizes several contrast-weighted images, the primary resources for radiological evaluations, in reduced scan time[3].

**SYNTHETIC MRI -** Synthetic MRI is a technique that synthesizes contrast-weighted images using quantitative relaxometer parameters measured from multi-contrast images. This approach is different from conventional MRI, which acquires specific contrast-weighted images (T2-weighted images [T2WIs]) per acquisition with no quantification. A typical synthetic MRI method measures longitudinal relaxation time (T1), transverse relaxation time (T2), and proton density (PD) parameters from which one can generate an arbitrary contrast-weighted image of the target echo time (TE), repetition time (TR), and inversion time (TI) using a signal model. This point of generating a synthesized image of the target parameters differentiates synthetic MRI from quantitative MRI[3]. The majority of MR syntheses are performed within two contrasts, such as generating

T1-weighted (T1w) MRI from T2-weighted (T2w) MRI[2]. Basic Synthetic MRI bundle includes the routinely used contrast weighted images such as T1W, T2W, PDW, T1W FLAIR, short TI inversion recovery, and T2W FLAIR[4].

While quantitative MRI is an important foundation of synthetic MRI, it is focused on producing quantitative maps (T2 maps) instead of synthesizing contrast-weighted images, although generating a contrast-weighted image from a quantitative map using a signal model is relatively straightforward([3]. It measures inherent T1 relaxation and T2 relaxation, which are absolute magnetic resonance properties of any living tissue. At the end of a single 6-minute scanning sequence, 2 parametric maps are generated based on magnetic properties of the tissue: R1 and R2 relaxation maps. R1 map is the inverse of the T1 map, and R2 map is inverse of T2 map where units of R1 and R2 are typically 1/s, and units of T1 and T2 are in milliseconds. Synthetic MRI uses quantitative probing of multiple physical properties to reconstruct various contrasts from one scan[4]. Synthetic contrast-weighted images are always generated from quantitative tissue parameters[3]. The majority of MR syntheses are performed within two contrasts, such as generating T1-weighted (T1w) MRI from T2-weighted (T2w) MRI[2]. Synthetic MRI is valuable because it synthesizes several contrast-weighted images, the primary resources for radiological evaluations, in reduced scan time[3].

**IMAGE INTENSITY STANDARDIZATION -** In conventional MRI there is a lack of image intensity standardization due to inherent differences in coil sensitivity, pulse sequence, and acquisition parameters. Signal intensity divergence from one examination to the next and the acquisition of different mappings from tissue properties to image intensity levels, impede direct comparison of absolute signal intensity values between examinations(4).

Quantitative MRI can overthrow this inconsistency along with an accurate appraisal of the physical characteristics of the tissue namely longitudinal R1 relaxation rate, the transverse R2 relaxation rate, and the PD(4). Quantitative MRI provides standardized measures of specific physical parameters that are sensitive to the underlying tissue microstructure. The standardized nature of these parameters facilitates comparison across sites and time points, which greatly improves the sensitivity and efficiency of multi - Centre and longitudinal studies(5).

**The Process of Synthetic MRI Have Following Steps-**

1. Acquisition - A single multi-parametric scan captures raw data that reflect the tissue's intrinsic properties(1). This is a saturation recovery prepared 2D FSE and is designed to acquire raw images that are necessary for quantitative T1, T2, PD, and B1 mapping. The sequence acquires images at 2 spin TEs and 4 saturation recovery times interleaved to generate multiple image contrasts, from which the spin parameters can be calculated(4). This sequence combines features of traditional T1 and T2 mapping in a single sequence(4). A least squares fit is performed on the signal intensity of these images to estimate longitudinal and transverse relaxation rates, PD, and B1 field inhomogeneity map(4).
2. Quantitative Mapping - The raw data are processed to generate quantitative maps of T1 relaxation time, T2 relaxation time, and proton density[1]. The quantitative maps were relatively noisy due to noise amplification throughout the reconstruction steps, limiting voxel-based interpretation[3].
3. Image Synthesis - Using these quantitative maps, algorithms synthesize various contrast-weighted images (T1-weighted, T2-weighted) that mimic traditional MRI scans(1). For the synthesis of contrast weighted images, a signal model that is fully determined by the quantified tissue parameters and sequence parameters[3]. In synthetic MRI, quantitative maps are not only displayed as outcomes but also utilized to generate contrast-weighted images. Quantified tissue parameters in combination with sequence parameters such as TE, TR, and TI are used to synthesize contrast-weighted images[3].

This approach reduces the scanning time and provides additional quantitative information that can be valuable for diagnosis and treatment planning(1).

**Parametric Mapping-** An inherent strength of Synthetic MRI is the acquisition and generation of T1, T2, R1, R2, and PD maps. The sequence allows for the calculation of absolute voxel wise R1 and R2 relaxivity and PD values via Synthetic MRI software (<60s processing time)[4]. Using QMRI created images without the variation in signal intensity that occurs when using conventional MRI acquisition where the contrast is dependent on the other pixel values in the image, making it possible to compare images between different examinations and different patients directly[4].

**Some Key Application Of Synthetic Mri Includes:**

1. Neurological Imaging: Synthetic MRI is particularly beneficial in brain imaging, where it can rapidly produce multiple contrast images essential for diagnosing conditions like multiple sclerosis, tumors, and stroke. Quantitative maps can help assess disease progression and treatment response(1). The parameters, which are objective and representative of the MR properties of the tissue of interest, have been utilized to investigate several CNS diseases(3). Quantitative maps obtained from MRF were used to diagnose hippocampal sclerosis (HS) in patients with mesial temporal lobe epilepsy (MTLE)The diagnostic rate was increased in the T1 and T2 maps of MRF compared with T1WIs, T2Wis, and FLAIR images from conventional MRI: most T1 and T2 values of HS lesions were higher than those of healthy control groups[3].
2. Musculoskeletal Imaging: In musculoskeletal radiology, synthetic MRI offers detailed images of joints, muscles, and bones[1]. Synthetic MRI techniques can generate arbitrary tissue contrast by modifying inversion, repetition, and echo times and have shown a high level of diagnostic agreement with conventional sequences in the knee, spine, and shoulder regions[6]. Synthetic MRI methods that generate multicontrast images, including quantitative maps, from a single acquisition may be one promising approach to overcome these

barriers[6]. It can evaluate conditions such as osteoarthritis, muscle injuries, and soft tissue tumors, providing both qualitative and quantitative data for a comprehensive assessment[1].

3. Oncological Imaging: Synthetic MRI is valuable in cancer imaging, specifically characterizing tumors based on their quantitative tissue properties. It aids in differentiating benign from malignant lesions and monitoring treatment efficacy[1].

4. Pediatric Imaging: For pediatric patients, reducing scan time is crucial to minimize the need for sedation. Synthetic MRI achieves this by generating all necessary contrasts from a single, fast scan, making it a child-friendly option(1). The generation of numerous sequences and quantitative data in a short scanning time is the most potential advantage of Synthetic MRI(7). Synthetic MRI offers a promising tool by quantification of brain tissue and revealing multi-contrast sequences in a single acquisition with a reasonable scan time, especially in young children[7].

5. Cardiovascular Imaging: Although less common, synthetic MRI is emerging in cardiovascular imaging to assess myocardial tissue properties. It can help diagnose conditions such as myocardial fibrosis and ischemic heart disease[1].

6. Research Applications: Synthetic MRI's quantitative approach makes it an excellent tool for research. It provides standardized, reproducible data for longitudinal studies and multi - center trials, advancing our understanding of various diseases[1].

7. Quantitative Data: The technique provides quantitative maps that offer objective, reproducible measurements of tissue properties, enhancing diagnostic accuracy(1). Within the Synthetic MRI software, there are multiple measuring tools. It is possible to measure tissue volumes in a region of interest defined by the user. The brain parenchymal fraction is a ratio based on intracranial volume, brain tissue, and CSF[4].

Flexibility: Synthetic MRI allows radiologists to synthesize any contrast-weighted image post-acquisition, providing the flexibility to make retrospective adjustments and reducing the need for repeat scans(1).

**Challenges And Future Directions -**

- While synthetic MRI offers many benefits, it also faces challenges. The accuracy of synthesized images depends on the quality of quantitative maps, and any errors in mapping can affect the final images. Additionally, widespread adoption requires training radiologists in interpreting synthetic images and integrating them into clinical workflows[1].
- Future developments in synthetic MRI aim to improve image quality, expand its applications, and enhance integration with advanced imaging techniques like functional MRI and diffusion tensor imaging. Ongoing research and technological advancements will likely address current limitations, making synthetic MRI an even more powerful tool in radiology[1].
- Despite the potential and promising performance in the literature, synthetic MRI has not been widely used in routine clinical practice, primarily because the addition of a synthetic MRI sequence without replacing existing sequences prolongs the total scan time. Therefore, the method used should be good enough to replace the corresponding existing sequences so that the entire scan time can be shortened. A major challenge is to generate high-quality synthetic images from quantitative tissue parameters[3].

**Advantages Of Synthetic MRI**

Efficiency: Synthetic MRI significantly reduces scanning time by generating multiple contrast-weighted images from a single acquisition, thereby improving patient throughput and comfort. This time-saving benefit is a significant advantage in the fast-paced environment of modern radiology, allowing for more patients to be seen and diagnosed in a shorter period[1].

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