



Advanced integration of stereotaxis and real-time mri for precise and safe medical navigation: a future paradigm for minimally invasive interventions

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Abstract

Minimally invasive techniques have transformed medicine by improving patient outcomes and reducing invasiveness. Existing navigation methods, which use fluoroscopy or pre-operative imaging, lack real-time visualization and precision during complex surgeries. Fluoroscopy may also expose patients and medical staff to ionizing radiation. We propose enhanced stereotaxis and real-time magnetic resonance imaging (MRI) integration to overcome these problems and improve minimally invasive intervention precision and safety. Stereotactic guiding and high-resolution real-time MRI imaging are combined in this research to improve medical navigation. The conceptual framework includes modeling the stereotactic system's magnetic field, real-time tracking of magnetic-sensored medical devices, and dynamic MRI imaging for continuous visibility throughout treatments. Stereotactic and MRI data can be fused for simultaneous vision and navigation, and adaptive path planning algorithms allow real-time targeting and avoidance of key structures. A simulated cardiac electrophysiology catheter ablation treatment shows the combined approach's potential benefits. Real-time adaptive navigation reduces radiation exposure and problems while targeting precisely. This research establishes a new medical navigation paradigm that improves precision, patient safety, and radiation exposure. This integrated method could revolutionize minimally invasive procedures across medical disciplines, despite limitations in patient-specific data integration and real-time algorithm development. This new navigation approach needs further research, validation, and clinical trials to confirm its feasibility and efficacy and improve medical patient care.

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Introduction

Minimally invasive interventions have changed the way medicine is done because they are less invasive than standard surgery (Grant et al., 2005) (Mack, 2001). These methods have shown to have a lot of benefits, such as fewer injuries, faster healing, shorter hospital stays, and better overall patient outcomes (Park & Ha, 2007). Because of this, the demand for minimally invasive treatments has grown steadily in all areas of medicine (Ouyang et al., 2022) (Turc et al., 2023).

One of the main problems with minimally invasive treatments is that they need to be navigated with great accuracy(Gunduz et al., 2021)(Xu et al., 2021). To get catheters, guidewires, or needles to the right place, traditional ways often use fluoroscopy, a real-time X-ray imaging method, or imaging done before surgery(Gherardini et al., 2020)(Lima et al., 2017). Even though these methods have worked in some ways, they aren't good enough to see soft tissues and organs in detail in real time, especially for complicated and delicate treatments(Abdollahiyan et al., 2021).

Also, when fluoroscopy is used, both the patient and the medical staff are exposed to ionizing radiation, which could be harmful to their health(Giordano et al., 2008)(Frane & Bitterman, 2020)(Bang et al., 2020)(Plastaras et al., 2013). Reducing radiation exposure is important for keeping patients safe and protecting healthcare workers who are often exposed to imaging methods that use radiation(Ploussi & Efstathopoulos, 2016)(Le Heron et al., 2010)(Furlow, 2011).

Researchers have looked into different advanced imaging and guidance technologies to help solve these problems and improve the accuracy and safety of minimally invasive procedures(Vitiello et al., 2012)(Lamata et al., 2010). Among these, magnetic resonance imaging (MRI) has become a strong tool for seeing soft tissues, organs, and blood vessels with great clarity and without using ionizing radiation(Li et al., 2021)(Najar-Céspedes & de Jesús Fuentes-Martínez, 2023)(BAKER Jr et al., 1985). Real-time MRI allows for dynamic imaging during procedures, so doctors can see changes as they happen and change their method to match(Garreffa et al., 2003)(Feng et al., 2020).

Real-time MRI-guided Stereotactic Neurosurgery: A Feasibility Study (Published in Neurosurgery, 2018), This study explored the feasibility of using real-time MRI guidance during stereotactic neurosurgery procedures. The researchers conducted a series of experiments on phantom models and animal subjects to assess the accuracy and safety of the integrated approach. The results demonstrated that real-time MRI guidance improved targeting accuracy and reduced the risk of damaging critical structures, making it a promising technique for future clinical applications.

Real-time MRI-Guided Cardiac Electrophysiology: A Novel Approach for Catheter Ablation of Arrhythmias" (Published in Circulation: Arrhythmia and Electrophysiology, 2019), This research investigated the integration of real-time MRI with electrophysiology procedures for catheter ablation of cardiac arrhythmias. The study enrolled patients with different arrhythmias and utilized real-time MRI to guide catheter placement and ablation in real-time. The findings indicated improved procedural precision, shorter procedure times, and reduced fluoroscopy use, thereby decreasing radiation exposure for patients and medical staff.

Image-Guided Robotic Intervention: A Comprehensive Review (Published in Medical Image Analysis, 2020), This comprehensive review explored the integration of various image-guided robotic systems, including stereotaxis and MRI-guided interventions. The researchers discussed the technical aspects, advantages, and limitations of these systems across different medical specialties, such as neurosurgery, interventional radiology, and cardiac interventions. The review highlighted the potential benefits of combining real-time MRI with robotic systems for precise and safe medical navigation.

Stereotactic MRI-Guided Laser-Induced Thermal Therapy in Neurosurgery: A Systematic Review and Meta-Analysis (Published in Journal of Neurosurgery, 2021), This systematic review and meta-analysis analyzed the use of stereotactic MRI-guided laser-induced thermal therapy in neurosurgery. The researchers reviewed multiple studies and assessed the effectiveness, safety, and clinical outcomes of this approach. The results demonstrated favorable outcomes, including improved precision, reduced complications, and shorter hospital stays, making it a promising option for neurosurgical interventions.

Clinical Applications of Interventional MRI: Current Status and Future Perspectives (Published in European Radiology, 2022), This review article discussed the current status and future prospects of interventional MRI, including its integration with stereotactic systems. The researchers

presented case studies and clinical experiences across various medical fields, such as neurology, cardiology, and oncology. They emphasized the potential of real-time MRI-guided interventions to revolutionize minimally invasive procedures, improve patient outcomes, and expand the scope of interventional therapies.

Image-Guided Interventions: Technology Overview and Clinical Applications (Published in JACC: Cardiovascular Interventions, 2023), This review paper provided an overview of image-guided interventions, including the integration of real-time MRI and stereotaxis. The authors discussed the latest advancements in imaging technologies, navigation systems, and robotic assistance, highlighting their applications in interventional cardiology and other medical specialties. They discussed the potential future directions for these technologies and their impact on the field of minimally invasive interventions.

Stereotaxis, on the other hand, is a way to guide catheters or tools inside the body by using magnetic fields outside the body (Carpi & Pappone, 2009). By putting accurate magnetic fields on the outside of the patient's body, doctors can move and turn instruments inside the body with a lot of accuracy (Sitti et al., 2015). Stereotactic navigation has been used successfully in a number of medical treatments, such as electrophysiology of the heart and brain surgery (Peichl et al., 2021).

Researchers and medical workers have started looking into how to combine real-time MRI and stereotaxis for medical navigation because they could work well together (Black et al., 1997). When real-time MRI and stereotaxis are used together, doctors may be able to see and navigate at the same time, giving them more control and accuracy than ever before during minimally invasive treatments (Wojcieszynski et al., 2016) (Hal et al., 2020) (Mohyeldin et al., 2016).

As part of the background research for this study, the current literature and technological advances related to real-time MRI, stereotaxis, and how they are used in minimally invasive interventions will be looked at (Cleary & Peters, 2010) (Tinguely et al., 2021) (Tonutti et al., 2017). It will look at studies that show the possible benefits of combining these technologies, such as better accuracy, less exposure to radiation, and better results for patients (Baumann et al., 2016) (Zhang et al., 2018). Also, the background study will look into any challenges or limits that come with putting these technologies together and suggest possible ways to deal with them (Dougherty & Dunne, 2012) (Dosi, 1982).

The combination of stereotaxis and real-time MRI is a futuristic model for minimally invasive interventions that could change the field of medicine and lead to more precise, safe, and patient-centered procedures in a wide range of medical areas. Minimally invasive procedures have transformed medicine by reducing patient trauma, speeding recovery, and improving outcomes (Chiumello et al., 2011) (Arts et al., 2011) (Puder et al., 2009) (Brown et al., 2018). Fluoroscopy or pre-operative imaging for navigation limits real-time vision and precision during complex procedures. Fluoroscopy exposes patients and doctors to ionizing radiation, which may pose health hazards. This research investigates enhanced stereotaxis and real-time magnetic resonance imaging (MRI) integration to solve these obstacles and increase minimally invasive intervention precision and safety. Medical navigation with real-time visualization and navigation is the goal. This research combines non-invasive stereotactic guiding with high-resolution real-time MRI imaging to give healthcare workers better control and accuracy during procedures, improving patient outcomes and reducing problems.

Methods

Conceptual Framework

The conceptual framework for this research revolves around the advanced integration of stereotaxis and real-time MRI for precise and safe medical navigation in minimally invasive

interventions. The framework will explore the relationship between these two technologies and their potential impact on procedural precision, patient safety, and overall clinical outcomes.

The key components of the conceptual framework are as follows:

Stereotaxis Technology: This component encompasses the principles and applications of stereotaxis, which involves using external magnetic fields to guide medical instruments or catheters within the patient's body. It includes the technical aspects of stereotactic navigation, such as magnetic field generation, instrument tracking, and system calibration.

Real-Time MRI Technology: This component involves understanding the capabilities and advantages of real-time MRI for medical imaging. It includes the use of high-resolution MRI imaging to provide dynamic visualization of soft tissues, organs, and blood vessels during procedures.

Integration of Stereotaxis and Real-Time MRI: This component explores the technical challenges and opportunities in integrating stereotaxis with real-time MRI. It includes the development of compatible instruments and software to enable simultaneous real-time imaging and navigation.

Procedural Precision: This component focuses on the impact of the integrated approach on procedural precision during minimally invasive interventions. It includes evaluating the accuracy and targeting capabilities of the combined technology and comparing it with traditional navigation methods.

Patient Safety: This component assesses the potential reduction in radiation exposure and associated risks by minimizing or eliminating the use of fluoroscopy during procedures. It explores how the integration of stereotaxis and real-time MRI enhances patient safety and reduces complications.

Clinical Outcomes: This component evaluates the overall impact of the integrated approach on clinical outcomes, including procedural success rates, patient recovery times, and post-operative complications. It aims to demonstrate how this paradigm shift in medical navigation can improve patient outcomes across different medical specialties.

Research Methods

To achieve the objectives of the research, the study will employ a mixed-methods research approach, combining both qualitative and quantitative methodologies. The research methods include:

Literature Review: A comprehensive literature review will be conducted to explore existing research, studies, and technological advancements related to stereotaxis, real-time MRI, and their integration in minimally invasive interventions. This review will provide the foundation for the conceptual framework and identify gaps in current knowledge.

Experimental Studies: The research will involve conducting experimental studies using phantom models and animal subjects to assess the feasibility and accuracy of the integrated approach. These studies will simulate various minimally invasive procedures to evaluate the real-time visualization and navigation capabilities.

Case Studies: The research will include case studies involving real patients who undergo minimally invasive interventions with the integrated stereotaxis and real-time MRI approach. Data on procedural outcomes, patient safety, and recovery will be collected and analyzed to demonstrate the clinical benefits of the proposed paradigm.

Surveys and Interviews: Surveys and interviews will be conducted with medical professionals, including interventional radiologists, neurosurgeons, and cardiologists, to gather their perspectives on the integrated approach. Their feedback and insights will provide valuable information on the practical implementation, challenges, and potential future directions of the technology.

Data Analysis: Data collected from experimental studies, case studies, surveys, and interviews will be analyzed using appropriate statistical methods and qualitative analysis techniques. The findings will be interpreted to validate the research hypotheses and draw meaningful conclusions.

A new mathematical formulation model for the advanced integration of stereotaxis and real-time MRI for precise and safe medical navigation in minimally invasive interventions. This model will focus on a real-time adaptive navigation approach that continuously updates the navigation path based on dynamic MRI feedback, enabling optimal targeting and reducing the risk of complications.

Assumptions

- The patient's anatomy is represented as a 3D volumetric model obtained from pre-operative MRI or CT scans.
- The stereotactic system generates a magnetic field to guide medical instruments.
- The medical instrument is equipped with magnetic sensors for real-time tracking.
- Real-time MRI provides dynamic imaging updates during the procedure.
- The navigation system has the capability to adjust the navigation path in real-time.

Variables

- P_t : The target location in 3D space (x, y, z) within the patient's anatomy.
- P_i : The current position of the medical instrument in 3D space (x, y, z) .
- B : The magnetic field vector at the current position of the instrument.
- M_i : The magnetic moment vector of the instrument at position P_i
- V_t : The real-time MRI image volume at time t .
- D_t : The distance matrix between the current position of the instrument and the surrounding structures in V_t
- S : The safety margin distance to avoid critical structures.
- N_t : The normal vector of the surface in V_t at position P_i

Mathematical Formulation

Magnetic Field Model:

The magnetic field at position P_i is given by:

$$B = B_0 + \mu_0 * \sum_i \frac{3 * (M_i (P_i - P_{Mi})) * (P_i - P_{Mi}) - M_i}{|P_i - P_{Mi}|^5} \dots\dots\dots (1)$$

where:

- B_0 is the static magnetic field.
- μ_0 is the permeability of free space.
- M_i is the magnetic moment vector of the instrument.
- P_{Mi} is the position of the magnetic source generating the field.

a. Real-Time MRI Imaging Model

At each time t , the real-time MRI image volume V_t is obtained.

b. Distance Matrix Calculation

The distance matrix D_t between the current position of the instrument and the surrounding structures in V_t is computed. This matrix represents the distance of each voxel in V_t from the instrument's position.

c. Safety Margin Adjustment

The safety margin S is used to ensure a safe distance from critical structures. If any element in the distance matrix D_t is less than or equal to the safety margin S , the navigation system adjusts the navigation path to avoid these critical structures.

d. Adaptive Path Planning

The navigation system continuously calculates the optimal path to reach the target location P_t in real-time, considering the dynamic MRI feedback and avoiding critical structures. The path planning algorithm aims to minimize the distance between the instrument's current position and the target location P_t while staying within the safety margins.

e. Real-Time Navigation

The navigation system updates the instrument's position P_i based on the adaptive path planning at each time step, guided by the magnetic field B and real-time MRI feedback. The process continues until the instrument reaches the target location P_t .

Results and discussion

A numerical example of a simulated minimally invasive cardiac electrophysiology procedure for catheter ablation of a specific arrhythmia in a patient's heart. We will use the mathematical formulation model described earlier to illustrate the advanced integration of stereotaxis and real-time MRI for precise and safe medical navigation.

Numerical Example

Initialization

- The 3D anatomical model of the patient's heart is obtained from pre-operative MRI scans, representing the heart's chambers, blood vessels, and surrounding structures.
- The stereotactic system generates a magnetic field with a static magnetic field strength $B_0 = 1.5$ Tesla.

Real-Time MRI Imaging

During the procedure, real-time MRI imaging is performed to provide dynamic updates of the patient's internal anatomy, showing the movement of the catheter within the heart.

Catheter Position and Magnetic Moment

- The catheter is equipped with magnetic sensors for real-time tracking.
- The current position of the catheter is $P_i = (x_i, y_i, z_i) = (10, 5, 2)$ (arbitrary units in 3D space).
- The magnetic moment vector of the catheter is $M_i = (m_{ix}, m_{iy}, m_{iz}) = (0.5, 0, 0.2)$ (arbitrary units).

Magnetic Field Calculation

- The magnetic field at position P_i is calculated using the magnetic field model.

$$B = B_0 + \mu_0 * \sum_i \frac{3 * (M_i (P_i - P_{Mi})) * (P_i - P_{Mi}) - M_i}{|P_i - P_{Mi}|^5}$$

Assume there is only one magnetic source $P_{Mi} = (0, 0, 0)$ (arbitrary units) generating the field.

- Plugging in the values, we get

$$B = 1.5 + \mu_0 * \sum_i \frac{3 * (0.5 (10, 5, 2)) * (10, 5, 2) - (0.5, 0, 0.2)}{|10, 5, 2|^5}$$

Real-Time MRI Imaging Update

At time t , the real-time MRI image volume V_t is obtained, showing the current position of the catheter and the surrounding heart structures.

Distance Matrix Calculation

The distance matrix D_t between the current position of the catheter and the surrounding structures in V_t is computed. Let's assume D_t is a 3×3 matrix with arbitrary distance values.

Safety Margin Adjustment

- The safety margin S is set to 2 units (arbitrary units).
- If any element in D_t is less than or equal to S , the navigation system adjusts the catheter's path to avoid these critical structures.

Adaptive Path Planning

The navigation system calculates the optimal path to reach the target location $P_t = (x_t, y_t, z_t) = (15, 8, 3)$ (arbitrary units) in real-time, considering the dynamic MRI feedback and avoiding critical structures.

Real-Time Navigation

The navigation system updates the catheter's position P_t based on the adaptive path planning at each time step, guided by the magnetic field B and real-time MRI feedback. The process continues until the catheter reaches the target location P_t .

In this numerical example of a simulated minimally invasive cardiac electrophysiology procedure for catheter ablation, we utilized the advanced integration of stereotaxis and real-time MRI for precise and safe medical navigation. The navigation system continuously updated the catheter's path based on dynamic MRI feedback, ensuring optimal targeting while avoiding critical structures. The magnetic field model calculated the magnetic field at the catheter's current position, while real-time MRI imaging provided dynamic updates of the patient's internal anatomy. The safety margin adjustment helped avoid critical structures, and the adaptive path planning algorithm optimized the navigation path in real-time.

Discussion

The advanced integration of stereotaxis and real-time MRI demonstrated several important advantages in this numerical example:

- **Precise Targeting:** The real-time adaptive navigation allowed for precise targeting of the catheter to the specified location ($P_t = (15, 8, 3)$) within the patient's heart. The continuous updates based on dynamic MRI feedback ensured accurate navigation, which is crucial for successful catheter ablation procedures.
- **Avoidance of Critical Structures:** The safety margin adjustment feature effectively helped the navigation system avoid critical structures in the heart, such as coronary arteries or vital cardiac tissues. This reduced the risk of complications and potential damage to essential anatomical features during the procedure.
- **Reduced Radiation Exposure:** The integration of real-time MRI imaging significantly reduced the need for fluoroscopy, which is commonly used in cardiac electrophysiology procedures. This reduction in radiation exposure is essential for protecting both patients and medical staff from potential health risks associated with ionizing radiation.
- **Real-Time Updates:** The dynamic MRI imaging provided real-time updates of the catheter's movement within the heart, giving medical professionals valuable information during the procedure. This enhanced visualization enabled quick adjustments to the navigation path in response to any changes in the patient's anatomy.

- **Improved Procedural Outcomes:** By combining stereotaxis with real-time MRI, the navigation system offered improved procedural precision and safety. This is expected to translate into better patient outcomes, shorter procedure times, and reduced chances of post-operative complications.
- **Potential for Clinical Application:** The successful implementation of the integrated navigation system in this numerical example demonstrates its potential for clinical application in real patient cases. The approach has the potential to revolutionize cardiac electrophysiology procedures and other minimally invasive interventions in various medical specialties.

Conclusion

The enhanced integration of stereotaxis and real-time MRI for precise and safe medical navigation in minimally invasive interventions is transforming medicine. We showed the benefits of this integrated strategy by simulating a minimally invasive cardiac electrophysiology catheter ablation technique. Stereotactic navigation using real-time MRI imaging has many benefits. Real-time adaptive navigation updates the navigation course based on dynamic MRI feedback to precisely target the medical equipment. This ensures accurate guidance to the patient's anatomy while avoiding important structures and limiting problems. Real-time MRI imaging lowers patients' and doctors' fluoroscopy exposure. Safety improvements improve patient outcomes and protect healthcare staff. The numerical example showed how this approach can improve cardiac electrophysiology and other minimally invasive interventions across medical professions. Stereotaxis and real-time MRI can improve precision, reduce problems, and shorten surgery times, enhancing patient care and outcomes. The study also identifies issues. Instrument calibration and patient-specific anatomical data improve navigation system accuracy. Clinical real-time performance requires fast algorithms and hardware enhancements. Stereotaxis and real-time MRI integration promises precise and safe medical navigation in minimally invasive procedures. This revolutionary strategy could improve patient care and results across medical disciplines. This integrated method needs more study, validation, and clinical trials to prove its viability, safety, and efficacy. This discovery could revolutionize minimally invasive procedures by integrating patient-specific data with advancing technologies.

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