Robotic instruments inside the MRI bore: key concepts and evolving paradigms in imaging-enhanced cranial neurosurgery

Sunil Manjila, Benoit Rosa, Karl Price, Rehan Manjila, Margherita Mancatelli, Pierre E Dupont

This is an author preprint. Full version of the paper : https://doi.org/10.1016/j.wneu.2023.01.025

Abstract:

Intraoperative MRI has been increasingly used to robotically deliver electrodes and catheters into the human brain using a linear trajectory with great clinical success. Current cranial MR guided robotics do not allow for continuous real-time imaging during the procedure because most surgical instruments are not MR-conditional. MRI guided robotic cranial surgery can achieve its full potential if all the traditional advantages of robotics (such as tremor-filtering, precision motion scaling, etc.) can be incorporated with the neurosurgeon physically present in the MRI bore or working remotely through controlled robotic arms. The technological limitations of design optimization, choice of sensing, kinematic modeling, physical constraints, and real-time control had hampered early developments in this emerging field, but continued research and development in these areas over time has granted neurosurgeons far greater confidence in using cranial robotic techniques. This article elucidates the role of MR-guided robotic procedures using clinical devices like NeuroBlate and Clearpoint that have several thousands of cases operated in a "linear cranial trajectory" and planned clinical trials, such as LAANTERN for MR guided robotics in cranial neurosurgery using LITT and MR-guided putaminal delivery of AAV2 GDNF in Parkinson's disease. The next logical improvisation would be a steerable curvilinear trajectory

in cranial robotics with added DOFs and distal tip dexterity to the neurosurgical tools. Similarly, the novel concept of robotic actuators that are powered, imaged, and controlled by the MRI itself is discussed in this article, with its potential for seamless cranial neurosurgery.

Introduction:

Intraoperative MRI has revolutionized linear-trajectory cranial robotics, generating several thousands of cases that have been operated thus far using devices like NeuroBlate and Clearpoint with enhanced safety and precision. Across the world, there has been an increasing use of intraoperative MRIs in glioma resections, focused ultrasound, and other procedures, validating its expanding clinical acceptance.[3, 14, 74, 20, 60, 63] The innovations in inside-the-bore MRI robotic technology demonstrate a positive trajectory for future growth. Figure 1 supports this with a graphic representation of PubMed search results for the relevant keywords, demonstrating an upwards trend over the past two decades (2000 – 2022).

Apart from the fact that MRIs offer non-ionizing multiplanar imaging with excellent soft tissue discrimination, the intraoperative MRI facilitates direct feedback about the progress of the procedure without requiring patient transportation out of the operating room, which carries morbid risks of endotracheal tube dislodgement and exposure to unsterile environments. However, in strict terms, the intra-operative MRI today is employed as a “near real-time MRI” in brain tumor resections because the patient is not stationed inside the MRI bore throughout the surgery, allowing real-time imaging whenever warranted. Rather than continuously taking real-time images, the patient is scanned once or a few times midway through the surgery and likely once after the completion of the procedure. In most settings, the surgery starts with a patient's pre-registered MR images taken prior to the day of surgery then being used the next day for contouring the lesion and trajectory planning for stereotactic intraoperative neuronavigation. With the resultant release of CSF and brain shifts, these images are not accurate once the brain dissection is in progress.[26] Although re-registration using intraoperative MR images that are acquired during surgery is readily possible today, there are not many institutions that can offer such continuous real-time MR imaging while the surgeon is working inside the MRI bore. This is partly due to the crowding of personnel and equipment in the MRI bore, as well as the arising compatibility issues of surgical instruments safely inside the MRI bore. Integration of robotic technology with MRI appears to allow images of sufficient quality, without requiring the surgeon to be constantly in the bore (remotely controlled) as in the case of devices like NeuroBlate and Clearpoint.[29, 37] Of mention, these are only linear trajectory procedures, which do not have or require bimanual dexterity at the tip of the instrument. Improvisation of primary MR image acquisition with thermographic images captured every 8 seconds, orthogonal display and a fifteen-millimeter thick, three-dimensional volume rendering perpendicular to the probe’s camera view with NeuroBlate are robust demonstrations of the uses of intraoperative MRI in cranial neurosurgery.

We propose that a robot located within the MRI bore itself assisting the surgeon, with additional distal tip dexterity and higher degrees of freedom (DoF) for the robotic tool can offer safety with precision. This will facilitate the surgeon accomplishing operative tasks with fewer instruments and retractors that go in and out of the surgical site while causing minimal tissue retraction injuries.

This article outlines the current scope and concepts of cutting-edge MR-conditional and MRI-powered robotic cranial neurosurgery. Additionally, the article discusses the ergonomic value in bringing the surgeon into the MRI bore and the robotic design characteristics that can render MR-conditional robotics possible. We highlight the technical challenges and latest developments of this field, apart from offering perspectives on its future.

Choice of MRI scanners in robotics:

In the early to mid-1990s, there were clinically used intraoperative MRI scanners in neurosurgery.[2] Of mention was the horizontal-field open-gantry MRI ("double-donut") system which was relatively convenient from the surgeon's access perspective (Fig 1a). Surgeons could continue to operate within the MRI field, although the weak MR field and gradient would fail to deliver truly high-quality MR images (Fig 1). MRI magnets for intraoperative use could be arranged in either a horizontal-field close or open gantry, as well as a vertical-field open gantry type. (Fig 1) These machines would move in on railroad-like tracks rather than the physical movement of the patient per se, on or off the OR table. With the same MR gradients and number of receiver coils using the 0.5T machines, the image quality was sub-par with these "double-donut" MR imaging, and surgeons did not favor these image acquisitions. After the initial shortcoming of classical huge open-bore intraoperative MR scanners with low Tesla strengths, the next challenge was to have the neurosurgeon perform the surgical tasks under accelerated real-time MR imaging with higher strength magnets.

Over the years, there have been several iterations of intraoperative MR imaging: a) the patient gets moved into a large single magnet bore or a double-donut bore where the entire patient fits in, b) the entire magnet moves into the operating room on the ground or along ceiling railroad tracks covering the patient when required, or c) the patient gets transferred into the adjacent MRI suite at any point during the surgery (with the risks associated with moving an intubated-ventilated patient). Developing off of these initial shortcomings, the ideal clinical situation realized was to have a neurosurgeon stationed in the MRI bore performing the surgery in the same magnetic field, whereby the cumbersome and risky transfer of the patient for real-time imaging can be circumvented. A solution to this problem could be achieved in a tri-fold manner: a) bring the double-donut framework of MRI bores to allow surgeons, robots, or both to have physical access to work in the magnetic field; (b) ensure at least 1.5T strength of the magnet as a trade-off between the speed of acquisition and image-quality; c) add multiple receiver coils across the head to provide a "parallel imaging technique" for superior image quality. Furthermore, ASTM International (American Society for Testing and Materials) proposed the FDA labeling criteria for portable objects that are allowed to be taken into the MR bore. The medical devices and instruments used in or near the MR environment should be labeled as MR safe, MR conditional or MR unsafe.[42] The MR safe label (square) indicates that the object or implant is safe in all MR environments. The item should be nonmetallic, nonmagnetic, nonconducting, and not a potential deflection hazard. The MR conditional designation (triangle) indicates that the instrument can be safely used in the MR environment; however, there are specific conditions for safe use that must be met with regard to the strength of MR system's static magnetic field (Bo) and the maximum static magnetic field gradient (dB/dx). The testing would be approved only for a precise model, make, and identification of the tested object. Finally, the MR unsafe label (circle) refers to a substantially ferromagnetic item, object, or device, the exposure of which would pose a significant safety hazard to the MR environment.

That being said, an ideally detailed description of zoning within the MRI scanner bore is beyond the scope of this paper.

Expectations of a cranial neurosurgical robot inside the MRI bore:

The aim of robotic surgery is to advance the accuracy, consistency, efficacy, and safety of procedures by uniquely employing tremor-free, fatigue-free, repeatable, bimanual, and precise operative techniques under magnified vision.[27] The intraoperative MRI provides not only visualization behind the surface anatomy but also excellent soft tissue discrimination, even outside the surgical site.[50, 51, 53] Therefore, MR-conditional robotics would complement the surgeon by providing real-time imaging, further adding to the precision and accuracy of the procedure. An entirely robotic surgery or robot-assisted surgery can be indicated by the need for fast computer processing beyond human capacity to allow remote tissue manipulation. This will avoid collateral damage to adjacent structures or support a surgeon executing a specific task under a limited operating field through the complex manipulation of hand-held tools. MRI guidance should offer continuous real time, nonionizing, and multiplanar imaging, leaving the surgeon to get in and out of the bore as efficiently as possible while surgical instruments remain in situ. A cranial neurosurgical robot in the MRI bore should thus allow the surgeon to operate in both steerable linear and curvilinear trajectories towards the clinical target. This holds potential for all invasive neurosurgical procedures, included but not limited to standard craniotomies, endoscopic surgeries, and even endovascular procedures (given the limited working space and crowding at the MRI bore).[1, 43, 64] There are many differences and similarities between traditional and MR-conditional robots. (Fig. 2)

In terms of overall structure, there are two broadly defined types of robotic systems possible. (Fig. 2) On one hand, hand-held and co-manipulated robots have a shared control architecture: the surgeon directly manipulates tools while robotic assistance is performed simultaneously.[45] Such systems, however, do not solve the flaws of manual tools, such as their manipulation in the constrained space of the MRI bore. On the other hand, console-based robots offer an architecture where no direct mechanical connection between the primary console and the secondary robot is present. This structure is preferable in the case of MR-guided robots since it avoids crowding the surroundings of the MRI bore. The surgeon manipulates a console and electrical signals are sent to the secondary robot present at the bedside. Console-based robots are often directly teleoperated, like in the case of the da Vinci system by Intuitive Surgical, which provides additional features of motion scaling and tremor filtering. Supervisory-controlled robots also exist where the trajectories are pre-planned and carried out at a distance from the robot. A depiction of the essential differences in the layout of console-based (telemanipulated) and hand-held (co-manipulated) robots in an MR-environment is shown in Figure 3.

Current status of clinical MR-conditional robots in cranial neurosurgery:

Today, there are over 40 robotic systems used in various neurosurgical procedures, whose creations date as far back as 1985, where the working trajectory was initially actuated using a modified Puma560 industrial robot (Advance Research and Robotics, Oxford, Connecticut) in a frame-based brain biopsy. Cranial neurosurgery has utilized many robotic devices since, such as the Neuromate (Renishaw UK), Rosa (Zimmer Biomet), Mazor X Stealth (Mazor), and more.[44] Only a handful of neurosurgical cranial robotic systems, however, are MR-conditional. One example is the NeuroArm, developed at the University of Calgary, which has been clinically tested. NeuroArm is an image-guided robotic system comprising of two robotic arms, each with at least six degrees of freedom, and cameras that provide 3-D stereoscopic views. The unique feature was that the MR images would be available during all phases of an operation (pre-, post- and intra-operative) without moving the patient. Over the past decade, there has been significant interest in MR-conditional techniques in nearly every subspecialty of neurosurgery, especially in endoscopy, tumors, skull base and functional neurosurgery. A few recent examples are depicted in Figure 7, demonstrating laser ablation of tumors and deep brain stimulation in the brain using the NeuroBlate (Monteris) and Clearpoint systems.

NeuroBlate specifically has been used in the US and Canada for MR-guided tumor ablations by laser via LITT. (Fig. 7) Over 3500 NeuroBlate procedures have been completed and more than two-thirds of these were in neuro-oncology. The MR-conditional robotic component has been the mainstay for its superior performance with enhanced safety and efficacy. LAANTERN (Laser Ablation of Abnormal Neurological Tissue Using Robotic NeuroBlate System) is a clinical study underway for robotic cranial procedures. For NeuroBlate, all linear and directional laser probe manipulations are actuated remotely at the workstation using the NeuroBlate Fusion-S software, while in MR-guided nonrobotic systems like Visualase all laser fiber linear manipulations are measured and done by hand with the patient in the MRI.[54] The Clearpoint robotic system is currently used in deep brain stimulation, intracranial biopsies, stem cell delivery and convection aided drug delivery in the brain. (Fig. 7)

These ongoing advancements to MRI robotics have led to expanding its clinical applications in neurosurgery through new functionalities, such as thermal mapping for the ablation of brain tumors. This, along with many other functionalities still require further innovations to the system, including improving their modelling algorithms to account for thermal dosages, trajectory calculations, faster system communications, closed-loop information feedback, reduced signal to noise ratio (SNR) as well as greater degrees of manipulation (1) and incorporation of new sensors technologies (5).(Sepaldeep)

These wider developments will in turn reduce the latency and other barriers to dynamic surgical robotics that can achieve high-level precision through motorized insertion axes that reduce targeting errors from misregistration or misalignment, and online trajectory correction methods that reduce surgery times, especially during bilateral procedures that can accommodate tandem registrations) (Squires, Ziyan Guo) (3,4). These innovations in serial kinematic chains of modern robotics led to development of next-gen robots like MINIR-II (Yeonjim) and similar fully actuated robotic assistants with interstitial high intensity needle based therapeutic ultrasound (NBTU)(Gang Li) (Niravkuamr Patel).

On the hardware side, MR-compatible robotic technology has become more articulate from those used in liver biopsies (Franco et al) with 4 DOF, prostate biopsies using (Grotenhius) 5 DOF, all the way to prostate MR robots with 6 DOF. Nuances from non-neurosurgical specialties have also been incorporated, especially from endovascular robotics (reference), intracardiac robotics (reference), breast biopsy robotics (reference) and spinal robotics like the SpinoBOT (ref). These innovations delve beyond pure hypotheticals and these have enabled real-world adoption of invaluable insights that can resolve sterilization issues, integrate water-cooling machinery, keep emergency management during the procedure and refine workflows by running unique case scenarios through appropriate clinical test cases (6).

Towards MR-conditional neurosurgical robots: challenges of designing robots and instruments inside the bore:

Like any robotic system, MR-conditional robots are a combination of actuators (e.g., motors), drive systems, and sensors, used in complex combinations to make a mechanism move in a controlled manner. The different components of MR-conditional robotic systems in OR settings are depicted in Figure 4. Furthermore, the system is usually interfaced with surgical instruments to carry out the task and placed on a gross positioning device that is used for placing the robot on the surgical site. What is different is the high magnetic field and gradients imposed by the MRI. Moreover, radiofrequency scanner signals may also interfere with metallic objects, causing some components to heat up to dangerously high temperatures. This phenomenon could be at least partly obviated by either reducing the MR gradients or switching pulses faster. Nevertheless, there is a trade-off between the choice of material, selection of magnet strength and position of the surgeon/robot in deciding the configuration of MR-conditional robots in neurosurgery. Each of the components forming the robotic system (actuators, drive systems, force/position sensors, image guidance, instruments, and positioning devices) must either be stationed inside the MRI room and be MR-conditional or be stationed far enough from the MRI field (or outside the room) in order not to interfere with it. (Fig. 4) In the past, such MR-conditional systems have been successfully built by using a cable transmission[2, 12], or a pneumatic/hydraulic line.[15]

MR-conditional materials:

Operating within close proximity of an MRI leads to a number of constraints.[7,10, 30, 36, 38] The high magnetic field prohibits any use of ferromagnetic materials within a few meters from the bore. If some ferromagnetic elements can be used at a distance (or properly anchored for avoiding being sucked into the center of the bore), elements that are introduced inside the patient close to the target might introduce artifacts in the imaging, reducing MR images quality in the vicinity of the anatomical targets.

MR-conditional actuators:

Conventional motors typically comprise ferromagnetic elements, and hence cannot be used in an MR environment.[4, 5, 13, 25, 75, 33, 34, 57, 73] There are two possible strategies to circumvent this problem to move parts in an MRI. The first possibility is to locate the actuation system outside the magnetic field influence, which is most often simply out of the room. MR-conditional drive systems, for instance using pneumatic or hydraulic lines, can then be used to transmit the motion to the robotic mechanism inside the MR.

Another possibility is to use MR-conditional actuators situated inside the MRI. This approach presents the advantage to be more accurate, since it prevents losses and inaccuracies introduced by a long drive system. However, the choice of actuators is greatly reduced by the MR-compatibility. Use of ultrasonic[47], piezoelectric[41, 65-68] motors has been reported. More recently, Ryu et al. proposed an optical actuated MR-conditional active needle based on shape memory alloys.[62] There are also recent developments in 3D printed designs, which allow creating complex mechanisms that are inherently MR-conditional. A striking example is the use of a hydraulically actuated compliant revolute joint based on multi-material additive manufacturing.[55]

MR-conditional sensors:

Like any robotic system, imperfections in the actuator and mechanism model make it such that using the motor output alone to control the robot would lead to unwanted parasite movements.

The classical solution to this problem is to close the loop by sensing the movement of the robot and changing the control output in accordance. Of notable importance is the use of optical sensors for position or force sensing.[70, 56, 62, 68] Such sensors can be embedded inside the surgical instruments and could lead to successful developments of MR-conditional force sensors for haptic feedback in neurosurgery in the future.

MRI-powered robots:

Classical robotic mechanisms and actuators are powered by energy sources such as pneumatic, hydraulic, or electric power.[24, 28, 31] Recently, studies have shown the possibility of powering robots directly through the MRI which allows simultaneous steering and imaging.[22, 23] (Fig. 5) The working principles are based on the fact that a ferromagnetic material is embedded in the mechanism, and the electromagnetic field gradients from the MRI are used to control its movements. The main advantage of such MR-powered robots is that the device can be tetherless, with a reduced footprint inside the MRI bore and control of the robot under direct MR image guidance. Conversely, the presence of ferromagnetic materials inside the robot structure can induce heating effects as well as artefacts. Therefore, the position of such elements must be carefully chosen in order not to hinder the procedure. Often this property of untethered millirobots can be used for tracking, producing focal hyperthermia and directional drug delivery.[19, 35]

At the moment, MR-powered robots have not been used in clinical settings. Studies, however, have shown a potential in many surgical areas, such as breast and brain biopsy and GI tract inspection.[12] Current developments look at steering millimeter and micro-meter sized elements to develop targeted drug delivery inside the human body under MRI guidance and control.

Research groups have investigated the use of pseudo-robots such as magnetotactic bacterium and nanocapsules which can be injected into the vascular system and guided with MRI to specific locations for tumor targeting and drug delivery. Though they are not artificial constructs, the bacterium functions in the same method as a tetherless mobile robot that can travel within the vascular channels.[35, 46]

Full potential of robots inside the MRI scanner: Rigid and Continuum robots:

Classical robots are typically composed of a series of rigid links connected by joints. This is the case, for instance, of the NeuroARM system.[69] While such robots offer high dexterity and precision, they are also often hard to maneuver in constrained space. In opposition, continuum robots present a continuous curvature and can bend at any point along their structure. Such robots are generally more suited for operations deep inside the body, where the anatomical constraints and a tortuous surgical corridor would be cumbersome with a rigid link robotic system. For instance, performing a posterior third ventricular mass biopsy using a rigid endoscope can bruise the fornix when accessed from the Kocher's point. Using a flexible endoscope allows maneuvering in such tight spaces, at the price of torque build up, but operating such endoscopes inside the MRI bore is extremely challenging. A curvilinear trajectory robot can traverse narrow brain corridors without damaging the eloquent areas of the brain.[43, 49] This can offer the advantages of flexible endoscopy with memory and waypoint selections. Continuum robots often take the form of a flexible body or backbone with an actuation system.[17, 21, 32, 39, 61] Pulling on one side one can make the flexible elements of the backbone bend and is often done using cables (tendon-driven), shape memory alloys, or pneumatic/hydraulic power. The flexible body or backbone can also be the flexible part of a catheter or of an endoscope. In this case, parts of the body bend passively upon contact with the anatomy, whereas others (often the distal part) can be actively controlled.

While the inherent flexibility of such designs can be an advantage (no damage to the surrounding tissues in case of inadvertent contact), it can also be an inconvenience (due to the necessity to reach specific curves and the inability to apply force at the distal tip). On the contrary, concentric tube robots (CTR), which have recently been proposed[6] allow applying distal forces. The general principle of CTR is to use a set of pre-curved superelastic telescoping concentric tubes that form the robot body. Tubes are rotated and translated with respect to each other in order to produce motion. Because of their unique features (large tool channel over outer diameter ratio with the ability to navigate without touching the anatomical structures and able to deliver forces at the tip suitable for surgical tissue interaction), these robots have been extensively studied in recent years, with applications in cardiac surgery[8, 9] and neurosurgery. MRI compatibility of the Nitinol and possibilities of MR-conditional actuation through piezoelectric actuation[11, 18] yield promise for future developments in neurosurgery.

Various surgeon-patient orientations in MR-conditional cranial neurosurgical robotics are shown in Figure 7. With the expanding scope of currently used MR-conditional robots in epilepsy, brain tumors and intracranial biopsy, the future of robotic technology looks extremely promising.[1, 71, 72, 48, 52, 40] Having several thousand intracranial MRI guided robotic procedures done already, there are emerging clinical trials, such as LAANTERN trial using NeuroBlate[37, 58] and Clearpoint's MR-guided putaminal delivery of AAV2 GDNF for a planned clinical trial in Parkinson's disease are also underway.[59] Clearpoint has already ventured into futuristic research on drug delivery into brainstem and merging DBS with viral vector stem cell implantation, among other innovative areas.

Most recent developments have advanced the technical capacity of MRI robotics and expanded their use cases. A significant development in the integration of these robots into the OR paraphernalia, which has seen success in prostate and breast biopsy procedures, in addition to highly precise applications in cranial and spinal neurosurgery.[76,77,78, 80,81,82] These successes provide the evidence for accelerated clinical testing, an increase in MRI surgical robotics in development like the CoBra or Stormram,[79,83,84] and rapid addition to the literature as seen on databases like PubMed. (Fig. 8)

Conclusion:

MR-conditional robots have the potential to provide the ergonomic comfortability for a neurosurgeon operating within the MRI bore, avoiding crowding within the bore and adding distal tool tip dexterity. Cranial robotics in the MRI bore can help executing specific tasks in a limited operating field without restricting complex manipulation of hand-held tools, offering added benefits such as tremor filtering, motion scaling and extreme precision. MRI enhances real time visualization of in-situ anatomy with non-ionizing multiplanar imaging with excellent soft tissue discrimination.

With several thousands of clinical cases operated using MRI-guided cranial robotics, and ensuing clinical trials of the same, we will soon usher in an era of “curvilinear trajectory” robotics enabling distal device tip dexterity to the surgical tools with real-time imaging as the prudent next step in progress. Having MRI-safe or conditional equipment, specifically trained personnel, the learning curve of the surgeon and capital budget can hamper the easy adaptation to neurosurgical robotics in the MR bore. However, optimization of clinical use, availability of cost-efficient robotic devices, and adequate training of neurosurgeons in this technology would catapult easy integration of MR-guided and MR-powered robotics into cranial neurosurgery.

References

1. Abdelaziz MEMK, Kundrat D, Pupillo M, Dagnino G, Kwok TMY, Chi W, et al. Toward a Versatile Robotic Platform for Fluoroscopy and MRI-Guided Endovascular Interventions: A Pre-Clinical Study. 2019 *IEEE/RSJ IROS*. 2019, pp. 5411-5418. https://doi.org/10.1109/IROS40897.2019.8968237
2. Abdelaziz S, Esteveny L, Barbé L, Renaud P, Bayle B, De Mathelin M. Development of a MR-compatible cable-driven manipulator: Design and technological issues. *Robotics and Automation* (ICRA), 2012 IEEE International Conference, pp. 1488-1494. https://doi.org/10.1109/ICRA.2012.6225302
3. Barnett GH, Voigt JD, Alhuwalia MS. A systematic review and meta-analysis of studies examining the use of brain laser interstitial thermal therapy versus craniotomy for the treatment of high-grade tumors in or near areas of eloquence: an examination of the extent of resection and major complication rates associated with each type of surgery. *Stereotact Funct Neurosurg*. 2016;94(3):164-173. https://doi.org/10.1159/000446247

4. Becker A, Felfoul O, Dupont PE. Simultaneously powering and controlling many actuators with a clinical MRI scanner. *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2014, pp. 2017-2023. https://doi.org/10.1109/IROS.2014.6942831
5. Bergeles C, Vartholomeos P, Qin L, Dupont PE. Closed-loop commutation control of an MRI-powered robot actuator. *IEEE International Conference on Robotics and Automation*, 2013, pp. 698-703. https://doi.org/10.1109/ICRA.2013.6630649
6. Boushaki M, Liu C, Herman B, Trevillot V, Akkari M, Poignet P. Optimization of concentric-tube robot design for deep anterior brain tumor surgery. 14th *International Conference on Control, Automation, Robotics and Vision* (ICARCV), 2016, pp. 1-6. https://doi.org/10.1109/ICARCV.2016.7838563
7. Bricault I, Jauniaux E, Zemiti N, Fouard C, Taillant E, Dorandeu F, et al. LPR: A Light Puncture Robot for CT and MR Interventions. *IEEE Engineering in Medicine and Biology Magazine*, Institute of Electrical and Electronics Engineers, 2008, 27 (3), pp.42–50. https://doi.org/10.1109/EMB.2007.910262
8. Burgner J, Swaney PJ, Lathrop RA, Weaver KD, Webster RJ. Debulking from within: a robotic steerable cannula for intracerebral hemorrhage evacuation. *IEEE Trans Biomed Eng*. 2013 Sep;60(9):2567-75. https://doi.org/10.1109/tbme.2013.2260860
9. Butler EJ, Hammond-Oakley R, Chawarski S, Gosline AH, Codd P, Anor JRTM, et al. Robotic Neuro-Endoscope with Concentric Tube Augmentation. *Rep U S*. 2012. https://dx.doi.org/10.1109%2FIROS.2012.6386022

10. Cardinale F, Rizzi M, d'Orio P, Casaceli G, Arnulfo G, Narizzano M, et al. A new tool for touch-free patient registration for robot-assisted intracranial surgery: application accuracy from a phantom study and a retrospective surgical series. *Neurosurg Focus*. 2017;42(5):E8. https://doi.org/10.3171/2017.2.focus16539

11. *Carvalho PA, Tang H, Razavi P, Pooladvand K, Castro WC, Gandomi KY, et al. Study of MRI Compatible Piezoelectric Motors by Finite Element Modeling and High-Speed Digital Holography. In: Lin MT. et al. (eds) Advancements in Optical Methods & Digital Image Correlation in Experimental Mechanics,* Volume 3. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, Cham. https://doi.org/10.1007/978-3-030-30009-8_16

12. Chapuis D, Gassert R, Ganesh G, Burdet E, Bleuler H. Investigation of a Cable Transmission for the Actuation of MR Compatible Haptic Interfaces. *The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, 2006. BioRob 2006., 2006, pp. 426-431. https://doi.org/10.1109/BIOROB.2006.1639125

13. Cheng SS, Desai JP. Towards high frequency actuation of SMA spring for the neurosurgical robot - MINIR-II. *IEEE International Conference on Robotics and Automation* (ICRA), 2015, pp. 2580-2585. https://doi.org/10.1109/ICRA.2015.7139546

14. Chen Y, Godage IS, Sengupta S, Liu CL, Weaver KD, Barth EJ, Webster RJ, III. An MRI-Compatible Robot for Intracerebral Hemorrhage Removal. *2017 Design of Medical Devices Conference.* Minneapolis, Minnesota, USA. April 10–13, 2017. V001T08A019. ASME. https://doi.org/10.1115/DMD2017-3451

15. Comber DB, Barth EJ, Webster RJ III. Design and Control of an Magnetic Resonance Compatible Precision Pneumatic Active Cannula Robot. *ASME. J. Med. Devices*. March 2014; 8(1): 011003. https://doi.org/10.1115/1.4024832
16. Couldwell WT, MacDonald JD, Thomas CL, Hansen BC, Lapalikar A, Thakkar B, et al. Computer-aided design/computer-aided manufacturing skull base drill. *Neurosurg Focus*. 2017;42(5):E6. https://doi.org/10.3171/2017.2.FOCUS16561
17. Eastwood KW, Looi T, Naguib HE, Drake JM. Design optimization of neuroendoscopic continuum instruments for third ventriculostomy and tumor biopsy. *Annu Int Conf IEEE Eng Med Biol Soc*. 2015;2015:4853-4856. https://doi.org/10.1109/EMBC.2015.7319480
18. El Bannan K, Chronik BA, Salisbury SP. Development of an MRI-Compatible, Compact, Rotary-Linear Piezoworm Actuator. *ASME. J. Med. Devices*. March 2015; 9(1): 014501. https://doi.org/10.1115/1.4028943
19. Erin O, Antonelli D, Tiryaki ME, Sitti M. Towards 5-DoF Control of an Untethered Magnetic Millirobot via MRI Gradient Coils. *2020 IEEE ICRA*. Pp. 6551-6557. https://doi.org/10.1109/ICRA40945.2020.9196692
20. Farooq MU, Cha K, Sohn DK, Yoo H, Ko SY. Design of a novel 6-DoF robotic system for pituitary tumor removal under MRI guidance. *2019 19th ICCAS*. 2019, pp. 456-459. https://doi.org/10.23919/ICCAS47443.2019.8971457
21. Farooq MU, Ko SY. A Stiffness-Changing Continuum Robotic Manipulator for Possible Use in MRI-Guided Neurosurgical Interventions. *2018 7th IEEE Int. Conf. on Biorob*. 2018, pp. 1260-1265. https://doi.org/10.1109/BIOROB.2018.8487892

22. Felfoul O, Becker A, Bergeles C, Dupont PE. Achieving Commutation Control of an MRI-Powered Robot Actuator. *IEEE Transactions on Robotics*, 31:2, pp. 387-399, April 2015. https://doi.org/10.1109/TRO.2015.2407795

23. Felfoul O, Becker AT, Fagogenis G, Dupont PE. Simultaneous steering and imaging of magnetic particles using MRI toward delivery of therapeutics. *Sci. Rep*. 6, 33567 (2016). https://doi.org/10.1038/srep33567

24. Fischer GS, Iordachita I, Csoma C, Tokuda J, DiMaio SP, Tempany CM, et al. MRI-Compatible Pneumatic Robot for Transperineal Prostate Needle Placement. *IEEE ASME Trans Mechatron*. 2008;13(3):295-305. https://doi.org/10.1109/TMECH.2008.924044

25. Gassert R, Yamamoto A, Chapuis D, Dovat L, Bleuler H, Burdet E. Actuation methods for applications in MR environments. *Concepts Magn. Reson*., 2006, 29B: 191-209. https://doi.org/10.1002/cmr.b.20070

26. Gonen L, Chakravarthi SS, Monroy-Sosa A, Celix JM, Kojis N, Singh M, et al. Initial experience with a robotically operated video optical telescopic-microscope in cranial neurosurgery: feasibility, safety, and clinical applications [published correction appears in Neurosurg Focus. 2018 Feb;44(2):E17]. *Neurosurg Focus*. 2017;42(5):E9. https://doi.org/10.3171/2017.3.FOCUS1712

27. Goto T, Hongo K, Kakizawa Y, Muraoka H, Miyairi Y, Tanaka Y, et al. Clinical application of robotic telemanipulation system in neurosurgery. Case report. *J Neurosurg*. 2003;99(6):1082-1084. https://doi.org/10.3171/jns.2003.99.6.1082

28. Guo Z, Dong Z, Lee K, Cheung CL, Fu H, Ho JDL. Compact Design of a Hydraulic Driving Robot for Intraoperative MRI-Guided Bilateral Stereotactic Neurosurgery.

IEEE Robotics and Automation Letters, 3:3, pp. 2515-2522, July 2018. https://doi.org/10.1109/LRA.2018.2814637

29. Gupta K, Cabaniss B, Kheder A, Gedela S, et al. Stereotactic MRI-guided laser interstitial thermal therapy for extratemporal lobe epilepsy. *Epilepsia*. 2020; 00:1-12. https://doi.org/10.1111/epi.16614
30. Hongo K, Kobayashi S, Kakizawa Y, Koyama J, Goto T, Okudera H, et al. NeuRobot: telecontrolled micromanipulator system for minimally invasive microneurosurgery-preliminary results. *Neurosurgery*. 2002;51(4):985-988. https://doi.org/10.1097/00006123-200210000-00024
31. Hovet S, Ren H, Xu S, Wood B, Tokuda J, Tse ZTH. MRI-powered biomedical devices. *Minimally Invasive Therapy & Allied Technologies*. 27:4, 191-202. https://doi.org/10.1080/13645706.2017.1402188
32. Ho M, Desai JP. Towards the development of a SMA-actuated MRI-compatible tendon-driven neurosurgical robot. *IEEE International Conference on Robotics and Automation*, 2012, pp. 683-688. https://doi.org/10.1109/ICRA.2012.6225323
33. Ho M, Kim Y, Cheng SS, Gullapalli R, Desai JP. Design, development, and evaluation of an MRI-guided SMA spring-actuated neurosurgical robot. *Int J Rob Res*. 2015;34(8):1147-1163. https://doi.org/10.1177/0278364915579069
34. Ho M, McMillan AB, Simard JM, Gullapalli R, Desai JP. Toward a Meso-Scale SMA-Actuated MRI-Compatible Neurosurgical Robot. *IEEE Transactions on Robotics*, 28:1, pp. 213-222, Feb. 2012. https://doi.org/10.1109/TRO.2011.2165371.

35. Iacovacci V, Lucarini G, Ricotti L, Dario P, Dupont PE, Menciassi A. Magnetic Bi-component Millirobot for Targeted Drug Delivery. *Hamlyn Symposium on Medical Robotics*, pp. 5-6, 2015.

36. Ito K, Toyama S, Gomi H, Kondo T, Aodai T, Shimizu T, et al. MR compatible manipulandum with ultrasonic motor for fMRI studies. *Proceedings 2006 IEEE International Conference on Robotics and Automation*, 2006. ICRA 2006., 2006, pp. 3850-3854. https://doi.org/10.1109/ROBOT.2006.1642291

37. Kim AH, Tatter S, Rao G, Prabhu S, Chen C, Fecci P, et al. Laser Ablation of Abnormal Neurological Tissue Using Robotic NeuroBlate System (LAANTERN): 12-Month Outcomes and Quality of Life After Brain Tumor Ablation. *Neurosurgery*. 2020 Sep 1;87(3):E338-E346. https://doi.org/10.1093/neuros/nyaa071

38. Kim D, Kobayashi E, Dohi T, Sakuma I. A new, compact MR-compatible surgical manipulator for minimally invasive liver surgery. *MICCAI 2002*, pp. 99-106. Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-45786-0_13

39. Kim Y, Cheng SS, Diakite M, Gullapalli RP, Simard JM, Desai JP. Toward the Development of a Flexible Mesoscale MRI-compatible Neurosurgical Continuum Robot. *IEEE Trans Robot*. 2017;33(6):1386-1397. https://doi.org/10.1109/TRO.2017.2719035

40. Landazuri P, Shih J, Leuthardt E, Ben-Haim S, Neimat J, Tovar-Spinoza Z, et al. A prospective multicenter study of laser ablation for drug resistant epilepsy - One year outcomes. *Epilepsy Res*. 2020 Nov;167:106473. https://doi.org/10.1016/j.eplepsyres.2020.106473. Epub 2020 Sep 22.

41. Lang MJ, Greer AD, Sutherland GR. Intra-operative robotics: NeuroArm. *Acta Neurochir Suppl*. 2011;109:231-236. https://doi.org/10.1007/978-3-211-99651-5_36
42. MacIntyre S. Regulating MR Safety Standards. *Radiol. Technol*. 2021 Sep; 93(1):75-89.
43. Maddahi Y, Gan LS, Zareinia K, Lama S, Sepehri N, Sutherland GR. Quantifying workspace and forces of surgical dissection during robot-assisted neurosurgery. *Int J Med Robot*. 2015 Jun 29. https://doi.org/10.1002/rcs.1679. [Epub ahead of print]
44. Marcus H, Payne CN. *Neurosurgical Robotics.* 2021, Vol 162, pp. 201-203. Springer US. https://doi.org/10.1007/978-1-0716-0993-4
45. Marcus HJ, Zareinia K, Gan LS, Yang FW, Lama S, Yang GZ, Sutherland GR. Forces exerted during microneurosurgery: a cadaver study. *Int J Med Robot*. 2014 Jun;10(2):251-6. https://doi.org/10.1002/rcs.1568. Epub 2014 Jan 16.
46. Martel S, Felfoul O, Mohammadi M, Mathieu JB. Interventional procedure based on nanorobots propelled and steered by flagellated magnetotactic bacteria for direct targeting of tumors in the human body. *Conf Proc IEEE Eng Med Biol Soc*. 2008;2008:2497-500. https://doi.org/10.1109/IEMBS.2008.4649707
47. Masamune K, Kobayashi E, Masutani Y, Suzuki M, Dohi T, Iseki H, et al. Development of an MRI-compatible needle insertion manipulator for stereotactic neurosurgery. *J Image Guid Surg*. 1995;1(4):242-248. https://doi.org/10.1002/(SICI)1522-712X(1995)1:4<242::AID-IGS7>3.0.CO;2-A
48. Mccracken DJ, Willie JT, Fernald BA, Saindane AM, et al. Magnetic resonance thermometry-guided stereotactic laser ablation of cavernous malformations in drug-

resistant epilepsy: Imaging and clinical results. *Operative Neurosurgery*. 2015;12(1):39-48. https://doi.org/10.1227/neu.0000000000001033

49. Moccia S, Foti S, Routray A, Prudente F, Perin A, Sekula RF, et al. Toward Improving Safety in Neurosurgery with an Active Handheld Instrument. *Ann Biomed Eng*. 2018;46(10):1450-1464. https://doi.org/10.1007/s10439-018-2091-x
50. Moser E, Laistler E, Schmitt F, Kontaxis G. Ultra-High Field NMR and MRI—The Role of Magnet Technology to Increase Sensitivity and Specificity. *Front. Phys*., 17 Aug 2017. https://doi.org/10.3389/fphy.2017.00033
51. Nycz CJ, Gondokaryono R, Carvalho P, Patel N, Wartenberg M, Pilitsis JG, et al. Mechanical Validation of an MRI Compatible Stereotactic Neurosurgery Robot in Preparation for Pre-Clinical Trials. *Rep U S*. 2017;2017:1677-1684. https://doi.org/10.1109/IROS.2017.8205979
52. Ostrem JL, Ziman N, Galifianakis NB, Starr PA, et al. Clinical outcomes using ClearPoint interventional MRI for deep brain stimulation lead placement in Parkinson's disease. *Journal of Neurosurgery.* 2016;124(4):908-916. https://doi.org/10.3171/2015.4.jns15173
53. Patel NA, Nycz CJ, Carvalho PA, Gandomi KY, Gondokaryono R, Li G, et al. An Integrated Robotic System for MRI-Guided Neuroablation: Preclinical Evaluation. *IEEE Trans Biomed Eng*. 2020;67(10):2990-2999. https://doi.org/10.1109/TBME.2020.2974583
54. Patel P, Patel NV, Danish SF. Intracranial MR-guided laser-induced thermal therapy: single-center experience with the Visualase thermal therapy system. *J Neurosurg*. January 2016:1-8. https://doi.org/10.3171/2015.7.JNS15244

55. Pfeil A, Siegfarth M, Geiskopf F, Pusch TP, Barbé L, Renaud P. Hydraulically-actuated compliant revolute joint for medical robotic systems based on multimaterial additive manufacturing. *International Conference on Robotics and Automation (ICRA)*, 2019, pp. 8401-8407. https://doi.org/10.1109/ICRA.2019.8793666
56. Polygerinos P, Puangmali P, Schaeffter T, Razavi R, Seneviratne LD, Althoefer K. Novel miniature MRI-compatible fiber-optic force sensor for cardiac catheterization procedures. *IEEE International Conference on Robotics and Automation*, 2010, pp. 2598-2603. https://doi.org/10.1109/ROBOT.2010.5509416
57. Raoufi C, Goldenberg A, Kucharczyk W. A new hydraulically/pneumatically actuated MR-compatible robot for MRI-guided neurosurgery. *2008 2nd International Conference on Bioinformatics and Biomedical Engineering*, 2008, pp. 2232-2235. https://doi.org/10.1109/ICBBE.2008.889
58. Rennert RC, Khan U, Bartek J, Tatter SB, Field M, Toyota B, et al. Laser Ablation of Abnormal Neurological Tissue Using Robotic Neuroblate System (LAANTERN): Procedural Safety and Hospitalization. *Neurosurgery*. 2020 Apr 1;86(4):538-547. https://doi.org/10.1093/neuros/nyz141
59. Richardson MR, Kells AP, Rosenbluth KH, Salegio EA, et al. Interventional MRI-guided putaminal delivery of AAV2-GDNF for a planned clinical trial in Parkinson's Disease. *Molecular Therapy*. 2011;19(6):1048-1057. https://doi.org/10.1038/mt.2011.11
60. Rich CW, Fasano RE, Isbaine F, Saindane AM, et al. MRI-guided stereotactic laser corpus callosotomy for epilepsy: distinct methods and outcomes. *Journal of*

Neurosurgery. 2021; Published online ahead of print. https://doi.org/10.3171/2020.7.JNS20498

61. Rucker DC, Webster RJ III. Statics and Dynamics of Continuum Robots With General Tendon Routing and External Loading. *IEEE Transactions on Robotics*, 27:6, pp. 1033-1044, Dec. 2011. https://doi.org/10.1109/TRO.2011.2160469
62. Ryu SC, Renaud P, Black RJ, Daniel BL, Cutkosky MR. Feasibility study of an optically actuated MR-compatible active needle. *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2011, pp. 2564-2569. https://doi.org/10.1109/IROS.2011.6094945
63. Sloan AE, Ahluwalia MS, Valerio-Pascua J, et al. Results of the NeuroBlate System first-in-humans phase I clinical trial for recurrent glioblastoma: clinical article. *J Neurosurg*. 2013;118(6):1202-1219. https://doi.org/10.3171/2013.1.JNS1291
64. Stoianovici D, Song D, Petrisor D, Ursu D, Mazilu D, Mutener M, et al. "MRI Stealth" robot for prostate interventions [published correction appears in Minim Invasive Ther Allied Technol. 2007;16(6):370. Mutener, Michael [corrected to Muntener, Michael]]. *Minim Invasive Ther Allied Technol*. 2007;16(4):241-248. https://doi.org/10.1080/13645700701520735
65. Su H, Cardona DC, Shang W, Camilo A, Cole GA, Rucker DC, et al. A MRI-guided concentric tube continuum robot with piezoelectric actuation: A feasibility study. *IEEE International Conference on Robotics and Automation*, 2012, pp. 1939-1945. https://doi.org/10.1109/ICRA.2012.6224550

66. Su H, Iordachita II, Tokuda J, Hata N, Liu X, Seifabadi R, et al. Fiber Optic Force Sensors for MRI-Guided Interventions and Rehabilitation: A Review. *IEEE Sens J*. 2017 Apr 1;17(7):1952-1963. https://doi.org/10.1109/JSEN.2017.2654489

67. Su H, Shang W, Li G, Patel N, Fischer GS. An MRI-Guided Telesurgery System Using a Fabry-Perot Interferometry Force Sensor and a Pneumatic Haptic Device. *Ann Biomed Eng*. 2017;45(8):1917-1928. https://doi.org/10.1007/s10439-017-1839-z

68. Su H, Zervas M, Cole GA, Furlong C, Fischer GS. Real-time MRI-guided needle placement robot with integrated fiber optic force sensing. *IEEE International Conference on Robotics and Automation*, 2011, pp. 1583-1588. https://doi.org/10.1109/ICRA.2011.5979539

69. Sutherland GR, Lama S, Gan LS, Wolfsberger S, Zareinia K. Merging machines with microsurgery: clinical experience with neuroArm. *J Neurosurg*. 2013 Mar;118(3):521-9. https://doi.org/10.3171/2012.11.JNS12877. Epub 20

70. Tada M, Kanade T. Design of an MR-compatible three-axis force sensor. *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2005, pp. 3505-3510. https://doi.org/10.1109/IROS.2005.1545371

71. Tovar-Spinoza Z, Ziechmann R, Zyck S. Single and staged laser interstitial thermal therapy ablation for cortical tubers causing refractory epilepsy in pediatric patients. *Neurosurgical Focus*. 2018;45(3):E9. https://doi.org/10.3171/2018.6.FOCUS18228

72. Voigt JD, Barnett G. The value of using a brain Laser Interstitial Thermal Therapy (LITT) system in patients presenting with high grade gliomas where maximal safe resection may not be feasible. *Cost Eff Resour Alloc CE*. 2016;14:6. https://doi.org/10.1186/s12962-016-0055-2y

73. Wang X, Cheng SS, Desai JP. Design, Analysis, and Evaluation of a Remotely Actuated MRI-Compatible Neurosurgical Robot. *IEEE Robotics and Automation Letters,* 3:3, pp. 2144-2151, July 2018. https://doi.org/10.1109/LRA.2018.2809447

74. Willie JT, Laxpati NG, Drane DL, Gowda A, et al. Real-time magnetic resonance-guided stereotactic laser Amygdalohippocampotomy for Mesial Temporal Lobe Epilepsy. *Neurosurgery*. 2014;74(6):569-585. https://doi.org/10.1227/neu.0000000000000343

75. Xiao Q, Monfaredi R, Musa M. Cleary K, Chen Y. MR-Conditional Actuations: A Review. *Ann Biomed Eng*. 48, 2707–2733 (2020). https://doi.org/10.1007/s10439-020-02597-8

76. Patel NA, Li G, Shang W, et al. System Integration and Preliminary Clinical Evaluation of a Robotic System for MRI-Guided Transperineal Prostate Biopsy. *J Med Robot Res*. 2019 Jun; 4(2): 1950001. https://doi.org/10.1142/S2424905X19500016

77. Lagomarsino M, Groenhuis V, Casadio M, Welleweerd MK, Siepel FJ, Stramigioli S. Image-guided Breast Biopsy of MRI-visible Lesions with a Hand-mounted Motorised Needle Steering Tool. IEEE ISMR 2021.

78. Dhaliwal SS, Wilby S, Firouzy S, et al. CoBra robot for localized cancer treatment and diagnosis under real-time MRI. AUTOMED 2021. https://doi.org/10.5281/zenodo.4923036

79. Dhaliwal SS, Belarouci A, Lopez MS, et al. CoBra: Towards Adaptive Robotized Prostate Brachytherapy under MRI Guidance. ICABME 2021 pg. 81-84. https://doi.org/10.1109/ICABME53305.2021.9604818

80. Li G, Patel NA, Burdette EC, Pilitsis JG, Su H, Fischer GS. A Fully Actuated Robotic Assistant for MRI-Guided Precision Conformal Ablation of Brain Tumors. IEEE ASME Trans Mechatron. 2021; 26(1): 255-266. https://doi.org/10.1109/tmech.2020.3012903

81. Kim Y, Cheng SS, Desai JP. Active Stiffness Tuning of a Spring-Based Continuum Robot for MRI-Guided Neurosurgery. IEEE Trans Robotics 2017; 1552-3098. https://doi.org/10.1109/TRO.2017.2750692

82. Squires A, Oshinski JN, Boulis NM, Tse ZTH. SpinoBot: An MRI-Guided Needle Positioning System for Spinal Cellular Therapeutics. Ann Biomed Eng. 2018 Mar; 46(3): 475-487. https://doi.org/10.1007/s10439-017-1960-z

83. Groenhuis V, Siepel FJ, Veltman J, Stramigioli S. Design and characterization of Stormram 4: An MRI-compatible robotic system for breast biopsy. IEEE IROS 2017; 928-933. https://doi.org/10.1109/IROS.2017.8202256

84. Pfeil A, Barbe L, Wach B, Cazzato RL, Gangi A, Renaud P. Observations And Experiments For The Definition Of A New Robotic Device Dedicated To CT, CBCT And MRI-Guided Percutaneous Procedures. Annu Int Conf IEEE Eng Med Biol Soc. 2018 Jul; 1708-1712. https://doi.org/ 10.1109/EMBC.2018.8512682

Table 1.		
Comparison of clinical and technical differences with usage of neurosurgical robots.		
	Hand-held robotic neurosurgery (co-manipulated)	**Console-based robotic neurosurgery (tele-manipulated)**
1	Surgeon stays closer to the field; sterile; in direct control operating the end-effectors.	Far away in the console, unsterile; not in direct control; more comfortable seating.
2	In emergency, no time lost in scrubbing up.	Needs time to get scrubbed.
3	Ergonomy: similar to existing surgical tools and classic surgical training; easier learning process.	Added features like internal articulations (“Endowrist”); hence learning curve is steep with extra-human DOFs.
4	Motion-scaling is less, not very precise.	More motion-scaling*, precise.
5	Difficult control of more than 2 arms.	Can easily control more than 2 arms by switching between them.
6	Certain degree of haptic feedback.	Haptic feedback currently in pre-human experimental set up only.
7	Less hardware and hence less operating and maintenance costs.	Significantly more expensive, more hardware.
8	Setting up time close to normal.	Longer set up time in the OR.
9	Easy to train surgical and anesthesia staff who are familiar with steps.	Surgical and anesthesia crew need training.
10	Part of the apparatus is non-robotic**, hence not a true “master-slave system.”	True “master-slave system.”
11	Standard incision sites and ports, uncompromised versatility***.	Different preoperative planning.
12	Stabilization achieved by additional positioning devices; difficult to implement tremor filtering.	Offers stabilization as a part of the robotic set up itself; tremor-filtering++.
13	Device does not occupy extra space in the OR.	Current machinery is bulky in dimension.

*For example, high motion scaling at console-based device means that a 2 cm movement of joystick would result in 1 cm movement in the surgical site, hence technique would be more accurate and precise.

**The handheld device can be moved in any direction, in a non-robotic pattern.

***Hand-held robotic surgery offers the familiar steps of non-robotic surgery, whereas in console-based robotics, certain ranges of motion would be different than how the surgeon would usually move his/her hands.

Table 1. Comparison of clinical and technical differences with the usage of neurosurgical robots.

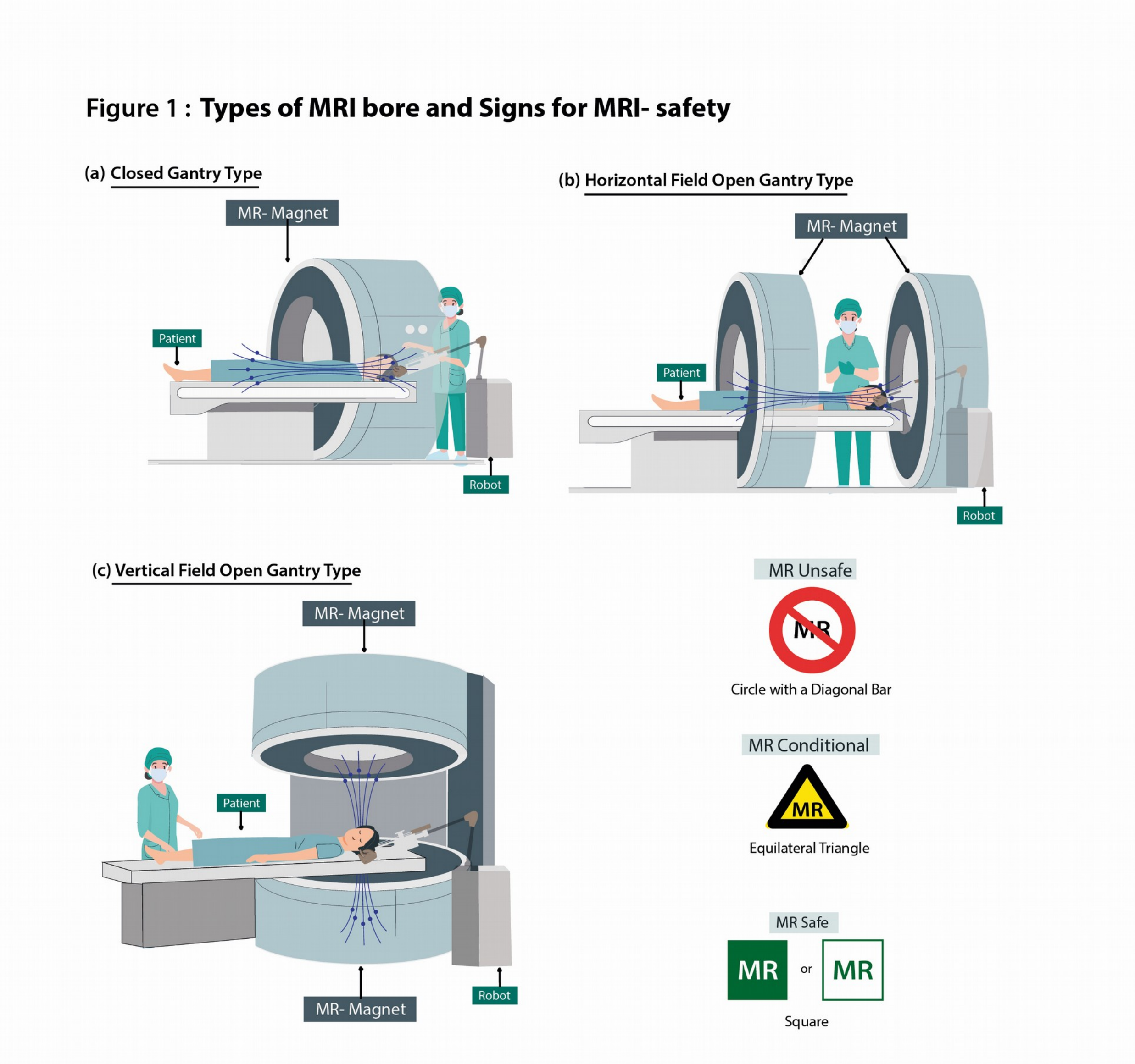

Figure 1. Different types of MRI bores and Signs for MRI safety (FDA labeling criteria by ASTM International).

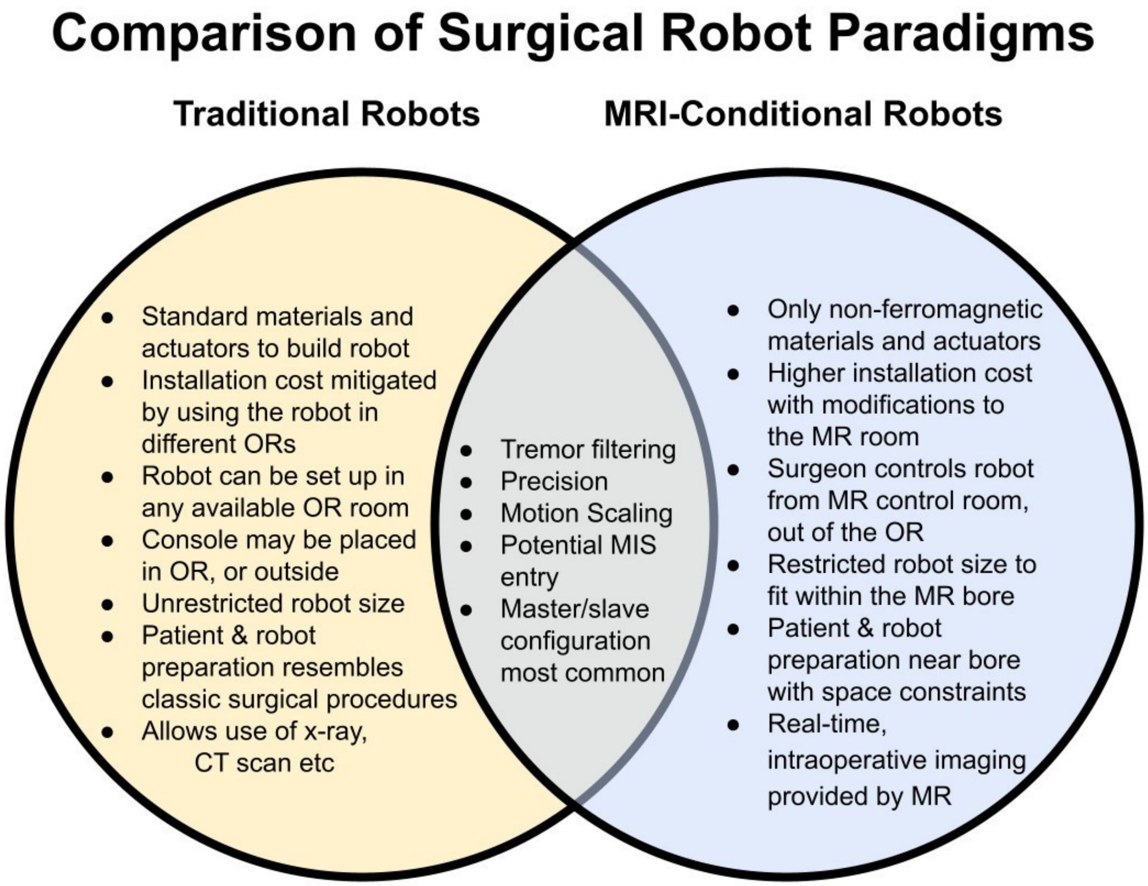

Figure 2. Comparison of surgical robot paradigms: traditional versus MR-conditional robots.

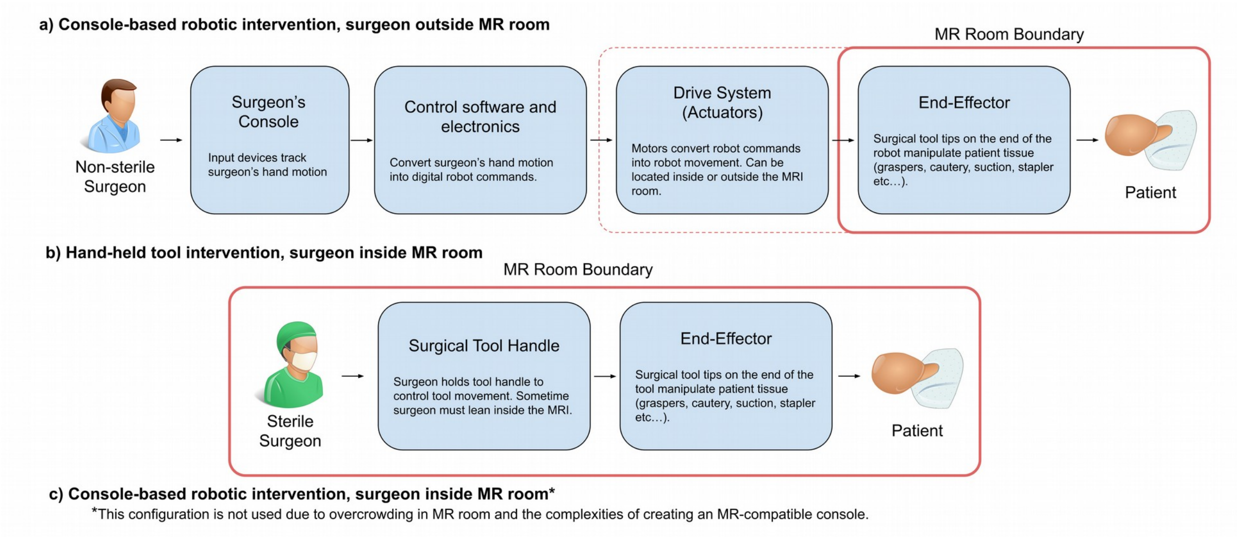

Figure 3. Comparison of Console based robotics (surgeon outside the MRI room) and hand-held tool robotics (surgeon inside the MRI room) in neurosurgery.

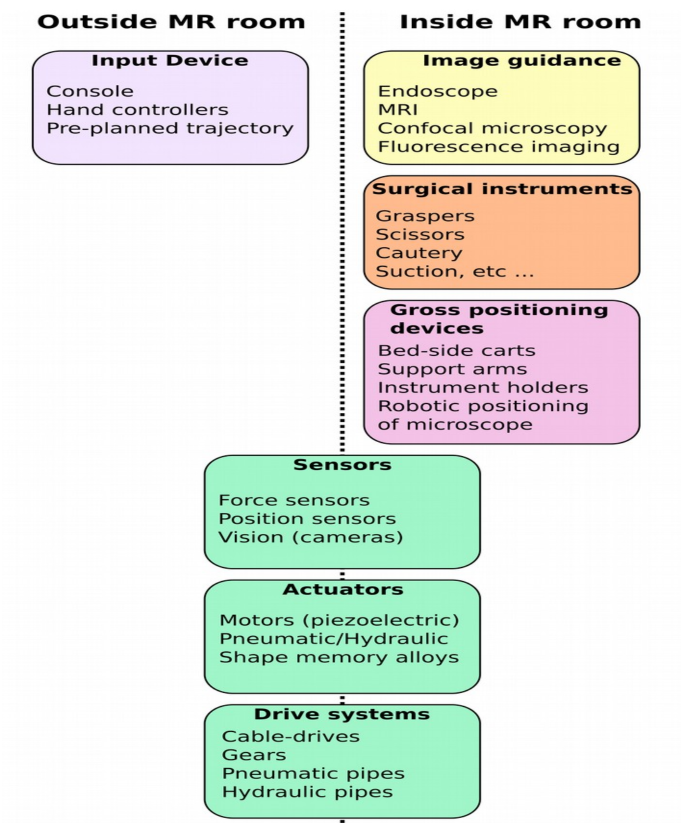

Figure 4. Components of MR-conditional robotic systems in an OR setting.

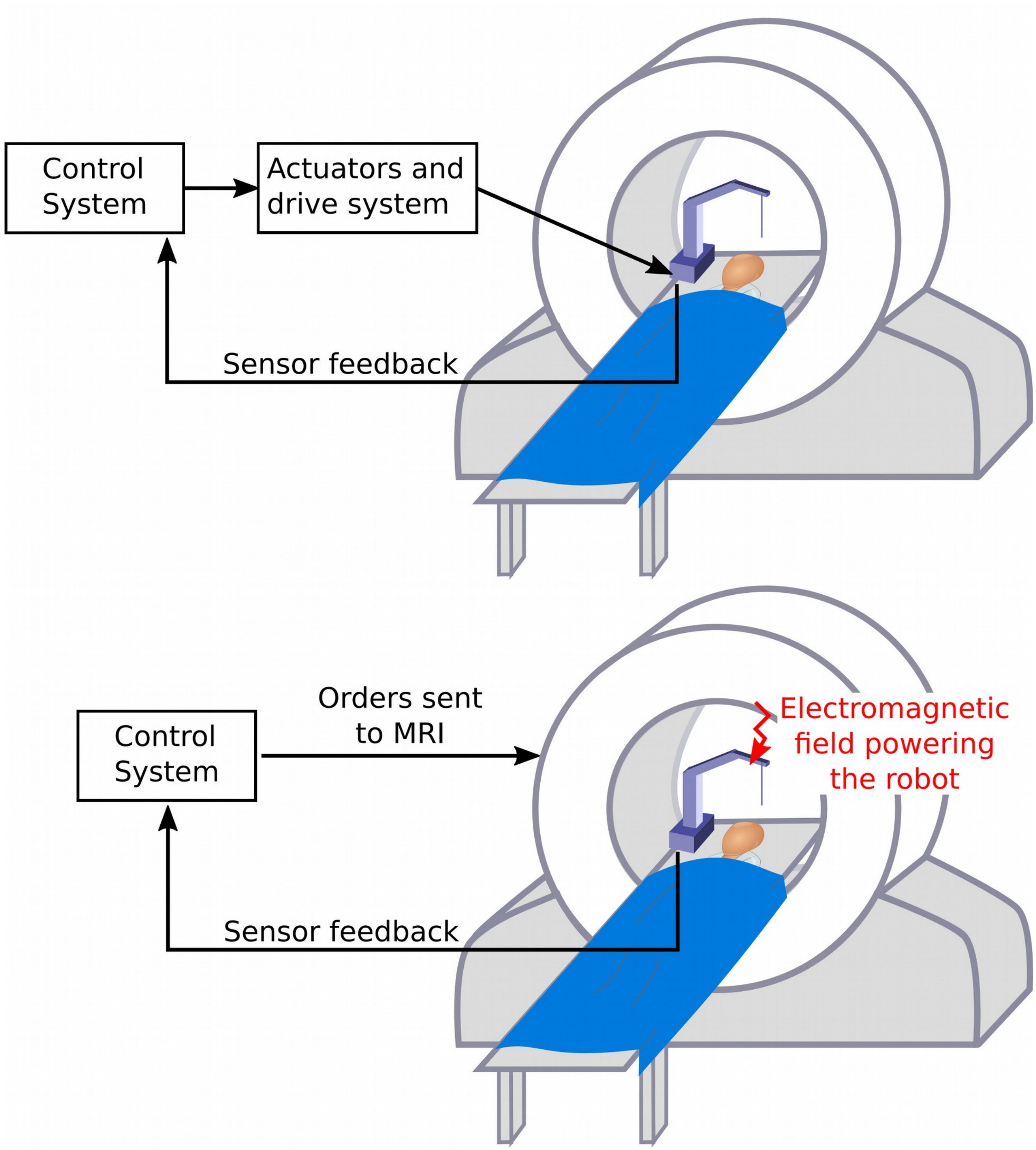

Figure 5. MR-conditional versus MR-powered robotic systems in cranial neurosurgery.

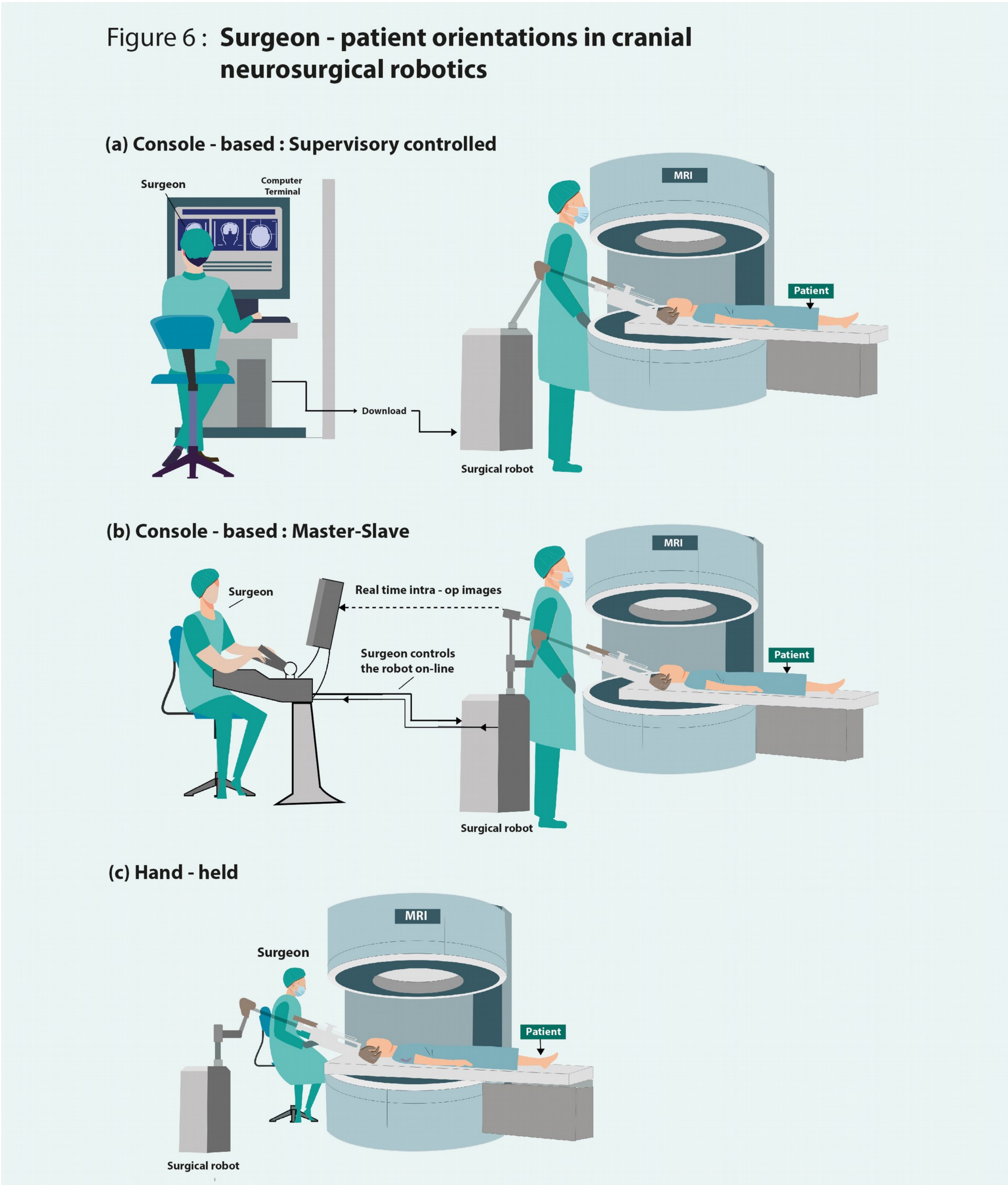

Figure 6. Depiction of surgeon-patient orientations with cranial neurosurgical robotics in a vertical-field open gantry MR scanner model.

Figure 7. Clinical MR-conditional robots: NeuroArm (non-commercial), NeuroBlate, and Clearpoint.

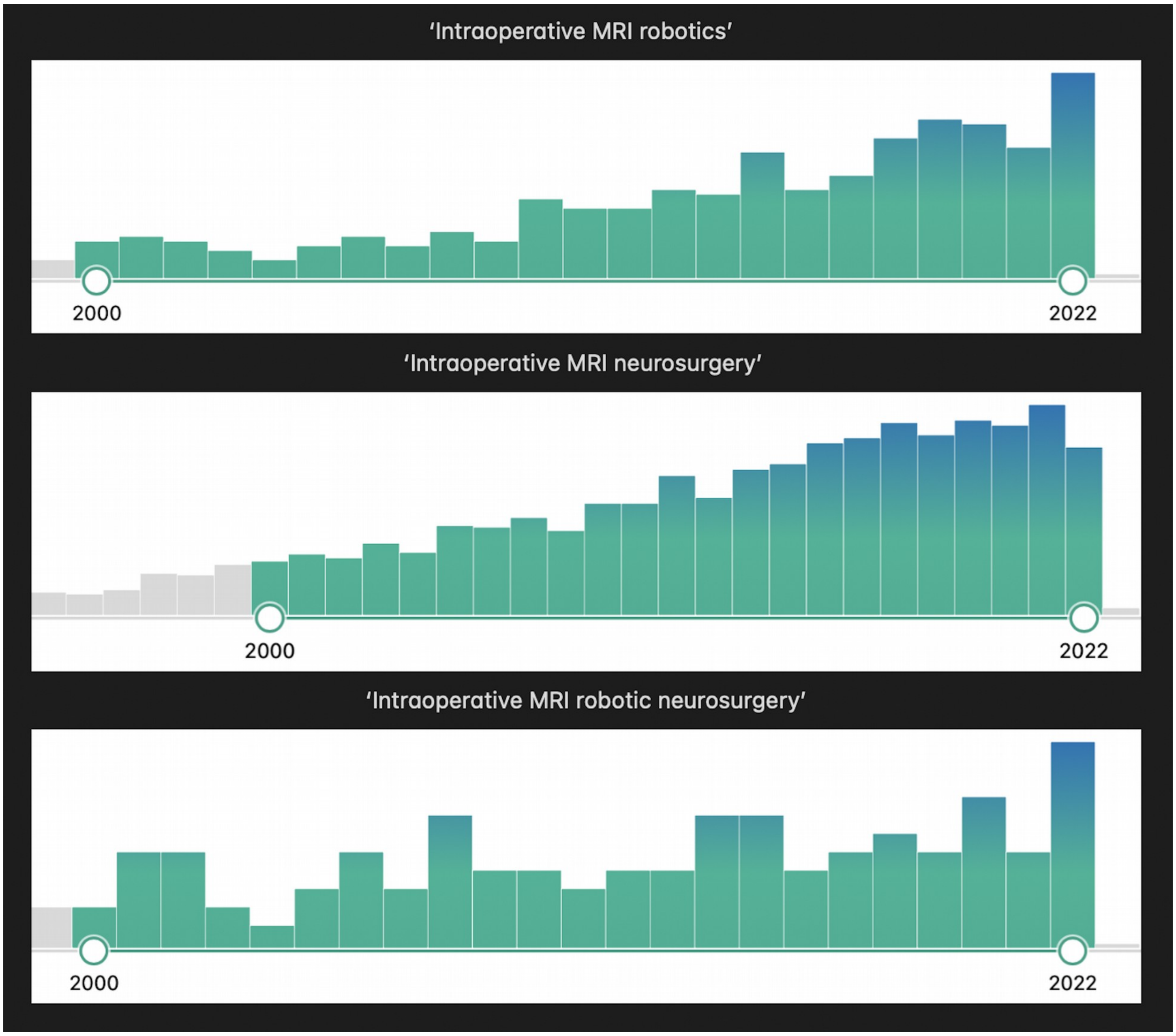

Figure 8. PubMed search result quantities for relevant MRI bore robotics key phrases from 2000 – 2022.