Future Directions of Robotics in Neurosurgery

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1 Introduction

Humans are improving the world thanks to exceptional intelligence, superiority, and efficiency in solving problems. Improvement in almost all relevant sectors has been remarkable and immensely supportive. Extensive developments in the medical sciences during the last few decades have helped to improve our life expectancy [1, 2] and provided us with superior health care. However, certain human limitations—mental, physiological, psychological, and physical—cannot be overcome with our present abilities. Accuracy, precision, and speed remain the most important aspects of our development and abilities. We have reached a stage where we require improvements beyond our physical and mental capabilities in these three aspects. Hence, numerous supportive and automated devices are being invented and developed to overcome these limitations on our development. The applications of computer machines with established systematic protocols have been automated since the previous century. Different uses of computational automation and robotics have now changed the world and our perception of its development. Robotics, once limited to the realm of imagination or science fiction, has become a reality and a tremendous benefit for humans in applications from heavy construction to precision-guided surgical procedures [3]. The potential of real-time application of robotics is unlimited and could entirely change the world as we see it today. Practical, precise, and cautious robotics applications could have far-reaching effects on human life. It is interesting that robotics has become part of both heavy and rough industrial applications and precisely conducted surgical processes for saving lives.

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2 Industrial Robots

The application of robotic systems is increasing because of the ease of operation, reduction of risks, reduced production or task completion time, improved automation, better precision, and capacity to avoid human errors. The development of artificial intelligence and computational learning has helped further in promoting the reliability of robotic tool performances [4]. The new age is industrial 4.0, and an industrial revolution has already occurred to integrate and apply digital information, mechanical information, and electrical and electronic processes for the further benefit of human life. Efficient and high-speed transmission and management of digital information is an important facet of this industrial revolution [5]. Similarly, artificial intelligence has had a major effect on improvements in the healthcare sector in the age of industrial revolution 4.0 [6]. Remarkable improvements in advanced sensor technologies, extended applications of artificial intelligence (AI), development of the internet of robotics things (IoRT), growing usage of cloud robotics, and improvement in the architecture of cognitive and cyber-physical robotics have built novel application platforms of advanced robotics [6]. Apart from these latest developments, the number of robotic applications is growing in various industrial contexts, including manufacturing, human–robot collaborations, and synchronous and cooperative robotic performance.

3 Robots in Surgery

Surgery is considered one of the most important responsibilities requiring pivotal precision, adequate professional training, accuracy, and timely decision-making. There are examples of outstanding surgeries that illustrate the remarkable ability and professional competence of a trained surgeon. However, in certain aspects, human efficiency requires adequate technological support for successful outcomes. The limitation of human vision is one such hindrance for delicate surgical processes. Other roadblocks include a high level of steadiness and other factors that can effectively determine the outcome of a procedure. Along with many extraordinary inventions, robotics has become one effective tool in improving visual capacity, steadiness, and improved precision in operations. Our current reliance on robotics has emerged gradually [7], it has been built on several failed attempts at applications and numerous intricate and complicated developments of sensors and communication technologies. In almost all complicated surgeries nowadays, robotic applications have found important roles and applications. These applications include robotic assistance and support in pediatric urology [8], hip arthroplasty [9], shape sensing and catheter control [10], general urological surgeries [11], complicated cardiological process such as the operation of the mitral annulus [12], and esophagectomy [13]. In complex procedures such as neurovascular surgeries [14], thymectomy [15], and ablation of abnormal neurological tissues [16], robotics has recently been used successfully.

3.1 History of Robotic Surgery

The urge to apply robotic techniques in complex and risky surgical procedures was initiated almost 30 years ago because of the requirement for better accuracy and precision, telepresence, and repetitive task completion in such procedures [17]. The first robot used in the operating theater was PUMA 200 (Westinghouse Electric, Pittsburgh, PA) in 1985. It obtained brain biopsies efficiently [18, 19]. The subsequent evolution of robotic systems helped in developing a "master–slave" human–robot system during the 1990s. Integration of computer-aided design and computer-aided manufacture (CAD-CAM) allowed better robots such as ROBODOC [20] to be developed; this was used extensively for arthroplasty and similar surgeries requiring precise 3D structural information for implantation. Remote controlling and precise instruction feeding became feasible during this development. Several important features of robotic surgery that transcended human abilities then allowed robotics to become a regular part of the operating theater. Such abilities included 3D vision, high-quality image streaming, image display with ease of understanding, physiological tremor filtering, runtime motion capturing and scaling, EndoWrist instruments, and other specialized features developed on the basis of specific requirements. The development and application of Automated Endoscopic System for Optimal Positioning (AESOP) during the 1990s, an effective telesurgical robot approved by the FDA, further raised expectations and the telecontrol of robots during major surgery [21]. No account of the progress of robotic surgery would be complete without mentioning the daVinci® surgical system, a total surgical robotic system that is now being used extensively throughout the world. It has been involved in six million surgeries since the 1990s (Source: Intuitive internal data).

3.2 FDA Evaluation and Regulation of Robotically-Assisted Surgical (RAS/RASD) Devices

The growing role of robotics in different aspects of surgery is inevitable following their successful implementation in improving patient care. However, "with great power comes great responsibilities." Excessive application of the latest robotic technologies could cause unwanted complications and compromise the overall goal of patient benefit and healthcare. Hence, proper regulatory measures need to be developed under strict guidelines, and the implementation and use of robotics in surgery should be monitored. Since the first approved robotic surgery using the AESOP system, the FDA has continuously developed guidelines and regulations for proper application of robotic surgical systems. All types of RAS have been clearly defined by the FDA as potentially containing the following:

1. A control system or console for the surgeon for better visualization and movement of the instruments.
2. Surgical instruments that are controlled by the surgeon from proximity or distance through a computerized system, which can have mechanical arms, camera, and similar instruments used for the surgery.
3. All supportive units including hardware and software, endoscope, pumps and suction units, electrosurgical units, and light sources.

The FDA has allowed precise applications by trained professionals for various types of regular surgeries using a robot-assisted system. Specific recommendations and mandates have been provided for healthcare providers and patients in relation to RAS/RASD. Healthcare providers have been instructed to report adverse events due to the use of RAS. However, the growing application of the RAS/RASD system for cancer patients compelled the FDA to publish additional safety regulations on February 28, 2019, which restricted the use of these techniques in some common cancer scenarios including hysterectomy, colectomy, and prostatectomy for patients having short-term (30 day) follow-ups [22, 23]. In response to growing reports of injuries due to robot-assisted surgery, the FDA has further improved the reporting system for authentic, verified information. A Medical Product Safety Network (MedSun) small sample survey was conducted by the FDA to update the regular challenges faced by modern surgeons responsible for handling RAS/RASD systems and for having a broad user viewpoint.

3.3 Surgical Robots and Telemedicine

Telemedicine has become a potential method of treatment in the digital age, benefiting the patient and the physician by saving time and allowing easy access to one-on-one communication. Telerobotics has become an essential part of telemedicine and various important surgical processes. Telerobotic systems are used for diagnostic methods such as USG (ultrasonographic) scanning and biopsy, and also for serious interventions including surgical processes. Though AESOP was used successfully during the 1990s, the Zeus robotic system was used for laparoscopy as the first robotic system for telesurgery in “Operation Lindbergh” in 2001 [24]. Telerobotics uses the “master–slave” approach to control the robotic system from far away. MELODY is an established telerobotics system that is being used successfully for multiple surgeries [25]. The main types of telerobot configurations include both simple serial and complex parallel robotic systems [26, 27], and specific types such as snakes [28] and Pop-Up manufacture of microelectromechanical systems (MEMS). A modern telerobotic system requires appropriate logical network architecture, enhanced connectivity, and an interruption-free network. Special attention should be given to real-time, high-quality live video streaming, data controlling, data storage, and information gathering. The present 4G data network connectivity is serving well; however, the 5G network and increasing implementation of the Internet of Things (IoT) could change the overall experience [29].

3.4 Application of Internet of Things (IoT) in Robotic Surgery

The increased application of internet-based technologies has allowed huge bodies of data to be exchanged in different forms between two or more connection points. The integrated technologies of the Internet of Things (IoT) have helped to connect multiple embedded systems and exchange crucial information even in a real-time situation. Furthermore, improved connectivity with 5G or beyond will improve such runtime data exchange and allow most tasks to be controlled remotely. Hence, such technological applications are finding excellent applications in distance-based robotic surgery, designated the Internet of Robotic Things (IoRT) [30]. Several recent reports suggest that attempts in this direction have already been initiated. In minimally invasive surgery, IoRT-based HTC VIVE PRO controllers for redundant manipulators were used for smooth human–robot interactions, and better performance was recorded [30]. Ishak and Kit recently reported the application of IoRT in robot-assisted surgeries [31].

3.5 Virtual Reality (VR) and Augmented Reality (AR) in Robotic Surgery

Virtual reality (VR) refers to interaction with a computer simulation-derived and artificially-generated 3D environment. It was initially popular in computer gaming. Soon it was realized that VR could be useful in a serious context such as live surgery monitoring rather than just for entertainment. Such customized simulation system protocols are immensely useful in modern-day critical training that is expensive and risky. Hence, VR-based technologies are being used extensively in simulation exercises for pilots as well as training robotic surgeons. Applications of VR for training laparoscopic surgeons have been reported [32, 33]. Several more recent applications of VR have also been reported for such training, surveyed extensively by Bric et al. and others [34]. Recent advances in specific surgical processes such as vesicourethral anastomosis and improving motor skills are also reported to have used VR-based techniques [35, 36]. Augmented reality (AR)-dependent methods are also being used for training surgeons to improve connections with the real world for a surgical process associated with robot-assisted surgeries such as neurosurgery [37] and others [38].

3.6 Artificial Intelligence (AI) and Deep Learning (DL) in Robotic Surgery

Artificial intelligence (AI) has revolutionized sophisticated modern data analysis methods and made information processing more meaningful and effective. The real-time application of AI is remarkable in almost all fields of science and technology. Broad and specific applications of AI technologies and algorithms such as Artificial Neural Network (ANN) and others have been reported from molecular biology to advanced medicine [39, 40]. AI is being used extensively in medical sciences and allied subjects [41], from the initial conversation with a patient through Chatbots to critical surgical operations. The futuristic telemedicine system is applying AI-derived technologies along with advanced robotics [42]. AI algorithms are now part of medical diagnosis, specifically in disease diagnosis from clinical images [43]; advanced deep learning tools are used to diagnose autism from MRI images [44]. Numerous similar successful applications have proved the efficiency of machine learning (ML) and deep learning (DL) technologies in medical problem-solving and improving diagnosis and patient care system.

4 Levels of Autonomy for Robotic Systems

As time passes, systems dependent on robotics and AI are becoming more reliable and autonomous in many ways. However, strict guidelines on the limit of autonomy are needed for these systems owing to concerns about extensive applications. Human interference is inevitable, and major decisions must be considered by humans. Restricted guidelines have recently been issued by the FDA in response to growing complaints from patients [22]. Nevertheless, specific robotic autonomy is the need of the moment, and it is challenging to design and develop such robots precisely [45]. Hence, complete autonomy is currently impossible. The different robotic systems used for surgeries are currently automated to different extents; for instance, the da Vinci® surgical system is operated under direct control, the ACROBAT system is managed under shared control, and supervised autonomy is followed for the CyberKnife system [46]. Therefore, the precise scope of autonomy should be defined in each case. Maximum automation could be allowed for repetitive and general mechanical tasks, whereas for certain delicate operations decision-making should be supervised by human experts.

5 Future Directions for Neurosurgical Robots

The robot has become an excellent technology for assisting neurological treatments. It is used in diagnosis, surgery, and rehabilitation (Fig. 1). The modern range of robotics has extended greatly from the earlier basic and general applications. Regarding future directions, this review-evidence demonstrates that the advanced tenet concepts and the development of neurosurgical robots had different origins but have progressed in parallel. Because of acceptance-driven developments including (1) advances in medical imaging technology, (2) engineering technological improvements such as control theory, sensors and actuators, (3) IoT and the 5G network, (4) smart materials, and (5) cell-based therapy and OMICS, they have finally joined. In future, they will progress together. Support from robotics-assisted systems has helped to improve patient care, prosthetics, orthotic device functioning, and surgical interventions. The patient's quality of life after surgery depends on neuroplasticity, a slow and steady process with neurorehabilitation. Hence, neurorehabilitation

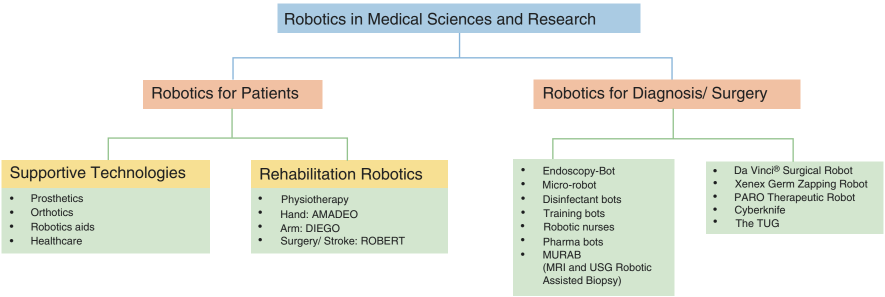

Fig. 1 Presentation of diverse categories of robotics currently implemented in medical sciences

requires constant care and monitoring of patients. These types of robotic assistance that are helping patients to gain normal or improved functionality of their limbs, improving their neuromuscular function, and so on, are enormously beneficial. COBOT, an abbreviation of Collaborative Robot, is specifically designed and programmed to work directly and interact with surgeons within the collaborative workspace. Its advanced features including hand guiding mode, safety monitoring, and power and force limitation represent the future trend for neurosurgical robots.

5.1 Focus on Enhancing the Overall Accuracy and Efficacy of Target Acquisition

5.1.1 Robots for Stereotactic Brain Biopsy and Spinal Surgery

Brain biopsies can be obtained successfully using modern robotic applications. Tissue samples are collected by navigating an advanced robotic system. A recent report by Dlaka and colleagues mentioned that a RONNA G3 robotic system successfully collected brain tissue through a sedan biopsy needle from a patient with B-cell lymphoma [47]. A systematic review Marcus et al. [48] on reports from the last 30 years suggested that stereotactic brain biopsy with robotic assistance is becoming common practice. However, a further detailed evaluation of processes conducted through robotic systems has been recommended for conclusive evidence. A study on 60 patients by Terrier et al. recommended that robot-assisted frameless surgery should be complementary to the frame-based surgical process [49]. The surgical process was safe and surgery time was reduced effectively. Enhanced safety was also noted for a semiautonomous stereotactic brain biopsy [50]. The introduction of novel minimally invasive robotics-based techniques for brain biopsy was feasible for most patients owing to their ease of operation, safety, better accuracy, and efficiency [51]. A similar robot-assisted process by the Neuromate robot (Renishaw, Gloucestershire, UK) was also considered for the brainstem biopsy of children and caused no complications [52]. Comparison of the minimally invasive robot-guided procedure with the manual arm-based protocol corroborated the safety, increased accuracy, and reduced operation time for the robot-assisted technique [53]. The evidence obtained on the growing reliability and safety of the robot-guided technique in operating complex brain biopsy is benefiting patients and surgeons. However, a case-to-case analysis is important and human expertise should not be ignored depending on the circumstances.

Apart from brain biopsy, advanced robotics is being increasingly used for spinal cord surgery. Spinal surgery is tedious and time-consuming, requiring a constant long-term detailed focus with a firm grip and understanding of three-dimensional neuromuscular structures. Advanced robotics with detailed 3D imaging and spinal reconstruction information and fine navigation systems can surely help to replace the required motor skills and repetitive tasks effectively, under careful supervision [54]. Analysis of the growing implementation of robotics applications in spinal surgery suggests that surgical accuracy has improved; nevertheless, the effect of radiation in relation to the robotic surgery type should be studied in detail for spinal surgery [55]. Recently, a real-time image guidance system for robotic assistance was successfully implemented in spinal surgery [56]. It provided better accuracy and improved surgical outcomes, and reduced collateral damage under expert supervision in most cases.

5.1.2 Robots in Intraoperative Imaging (CT/MRI)

Imaging techniques such as computed tomography (CT) scans and magnetic resonance imaging (MRI) are integral to modern pathological diagnosis. These techniques are superior and efficient in most cases. Robot-guided stereoelectroencephalography (sEEG) with 3T MRI conducted on five patients suggested that the process can reduce the radiation exposure of patients and is safe, with improved accuracy in 1.5T MRI [57]. Superior accuracy has been reported for the robotic system associated with tomographical imaging for surgery [58]. Chenin et al. suggested that the Robotic Stereotactic Assistance (ROSA) technique along with flat-panel computed tomography (fpCT) provided higher accuracy in pedicle screwing for circumferential lumbar arthrodesis [59]. Coupling sophisticated imaging techniques with robotics helped to augment accuracy and maintain safety and good patient outcomes. Like CT, MRI has also been coupled with robotics for better results. An integrated system combining MRI and robotics, Stormram 3, has been developed for breast biopsy [60]. Similar MRI and robotics-coupled technology has been developed for neurological rehabilitation [61].

5.1.3 Robotized LASER Ablation

LASER ablation is a minimally invasive procedure for targeted microsurgery of tissues, removed by an iMRI-guided targeted laser. This surgical process has been used frequently for localized tumors such as brain tumors. Currently, ROSA is being used for better targeting and focusing during the ablation process. This technique has been applied to intractable epilepsy [62], necrosis of the posterior cranial fossa [63], and other conditions. Integrated global efforts such as LASER Ablation of Abnormal Neurological Tissue using Robotic NeuroBlate System (LAANTERN) have been developed for better application and analysis of LASER ablation surgery such as brain tumor ablation [64], and safety of Stereotactic LASER ablation (SLA) for intracranial lesions [16]. LASER ablation has emerged as a state-of-the-art procedure for targeted surgical removal of tissues. Further studies and detailed analysis of the results of more cases will provide useful information on the specific success of this technique.

5.2 Focus on Enhancing the Neurosurgeon's Capabilities

5.2.1 Robots for Craniotomy

At present, craniotomy is mostly conducted using semi-automatic tools. The manual process entails many risks including shaking, recoil motion, and others that can affect the outcome of this high-risk procedure. The kinematic process has been optimized and used for robotic applications with better results. Reconfigurable parameters have been studied keenly and a Spherical Parallel Mechanism (SPM) has been proposed for better kinematics during craniotomy through robotic assistance [65]. Development of human–robot interactions and collaborations for craniotomy has been reported [66]. Experiments have been conducted on cadavers to elucidate the kinematics and the force optimization for craniotomy using a long-distance teleoperated robot [65]. Robotics now serves as a regular instrumental process for craniotomy. In the future, with more kinematic studies and optimization, improved automation and skillful implementation will be possible for serious cases.

5.2.2 Robots for Interventional Neurosurgery

Implementation of robotics coupled with interventional MRI was attempted previously [67]. Surgical prototype development and improved accuracy were attempted to achieve better and more reliable implementation of robotics in neurosurgery [68, 69]. Robotics is now regularly used in cerebrovascular and endovascular neurosurgery and is helpful in processes such as intraoperative imaging, catheter introduction and guidance, and navigation [70].

5.2.3 Robots for Endoscopic Endonasal Transsphenoidal Approach

The endoscopic endonasal transsphenoidal approach is a minimally invasive technique for surgical treatment of intrasellar lesions and pituitary adenomas. The transsphenoidal midline-route pathway to reach the intrastellar region offers a sufficient workspace with endoscope-enhanced illumination and panoramic wide-angled view of the supersellar and parasellar portions of intrasellar lesions. When the endoscopic endonasal transsphenoidal approach was first introduced, insertion of an endoscope was a key challenge for neurosurgeons. The development of surgical techniques and improvement of instruments made this approach more promising. Its limitations are surgical difficulties and instrument dexterity. Neurosurgeons have to be tremendously skillful because they operate in a narrow workspace and must be able to reach the exact target, which remains surrounded by eloquent structures including major vascular and neural structures. A human error such as a slight deviation of the tools can lead to undesirable and even fatal consequences. This indicates the requirement for new modalities to assist neurosurgeons. Implementation

Fig. 2 Presentation of the implementation of robotics for the endoscopic endonasal transsphenoidal approach in a cadaveric study

of robotics for the endoscopic endonasal transsphenoidal approach was attempted in a cadaveric study (Fig. 2). This technology is now considered a crucial modality, with some preclinical research teams working to develop prototype robots. For designing a robot to guide the endoscopic endonasal transsphenoidal approach, the following significant points must be considered: (1) the automation of the task must save time for the neurosurgeon and enhance their competence, (2) the robot must be reliable, i.e. must have in-depth knowledge of the workspace and types of interactions between the instruments it holds and the tissues, and (3) the robot must be very small and easy to install in the operating room, and easily maneuverable by the surgeon [71]. The first cadaveric trial of a robot-guided endoscopic endonasal transsphenoidal approach showed a significantly shorter initial setup process and time of operation than the conventional manual approach [72–75].

5.3 Outlook for the Neurosurgical Robot

The growing application of advanced robotics in neurosurgery and other complex operating procedures provides extensive benefits to patients and neurosurgeons, and helps in reducing procedural complications and probable human errors by focusing on the overall accuracy of neurosurgical procedures and enhancing neurosurgeons' capabilities. However, the improvements are ongoing and require further precise changes in the future. Several significant factors that should be considered are discussed below. First, advanced intraoperative imaging should be included to access, monitor, analyze, and understand real-time data without any interruption or compromised image quality. Image quality and filtering of mechanical shaking in real time are important and can decide the outcome of the neurosurgical process. Second, successful and result-oriented human–machine interface development is essential; proper simulation even with 3D printed models and guided practice should be accessible for training neurosurgeons. Precision can be improved with better 3D image quality, image streaming speed, and processing, minute operating, and distance-based control of the systems during a procedure. Third, the improvement of a parallel network of robotic systems and better data transfer through IoT with the 5G network will yield enormous benefits for operations and neurosurgical work. The autonomy of the robotic systems should be decided after detailed evaluation of individual process and requirements. Further improvement in the autonomy of robotic applications will improve outcomes. Last but not least, reducing the cost of the neurosurgical robot can make the surgeries affordable for most patients. Finally, the effect of the COVID-19 pandemic on surgical practice is a crucial example of its widespread impact on the workforce, staffing issues, procedural prioritization, and interoperative viral transmission risk [76].

Besides the future value of the neurosurgical robot in enhancing the accuracy of neurosurgical procedures and neurosurgeons' capabilities, the effect of the COVID-19 pandemic on neurosurgery is a matter of concern. Most neurosurgical procedures including spine and cranial procedures are safe to perform with strict PPE, but the involvement of neurosurgical robots has to be investigated. PCR testing for COVID-19 is recommended for suspected patients before surgery and the indicated patient should be operated as gently as possible in a negative pressure operating room. To reduce bone aerosol, cranial and spinal drilling should be performed meticulously under robotic assistance. Furthermore, endonasal procedures should be avoided because of significant aerosol droplets and the risk of viral transmission [77, 78].

In this hazardous and uncertain situation, there is a greater role for the robot to enhance health care provider safety, though there are recommendations for prioritization of procedures that involve robotic surgery with the validation guidelines and alterations to operative techniques. To maximize protection for healthcare providers and minimize collateral damage to COVID-19 patients requiring surgery, the robot is needed for procedure-specific reduction of bone aerosol, shortening the time for attaining the target, and distancing the infected patient from the surgical team. Moreover, under robotic-assisted neurosurgery, operations are undertaken only by the most experienced surgeons with the minimum number of staff in the OR. Also, other recommendations need to be followed including (1) adequate use of PPE for all patients, with higher levels of PPE for all healthcare providers, (2) careful selection of patients for all elective surgery, (3) postponement if possible, and (4) minimizing aerosol dispersal.

6 Conclusion

Robotic-assisted neurosurgery has emerged as great support for diagnosis and surgical procedures. It has reduced complex neurosurgical timings and the risk of human error, enhanced the remote control of operation procedures, and increased the affordability and accessibility of a better and more reliable health system. Apart from neurosurgery, robot-assisted systems are being considered for other areas of surgery including gynecological, cardiological, urological, transoral, thoracic, and many more. Enhanced simulation training, and a growing number of professionals with hands-on robot training-assisted neurosurgery, will aid in managing a large pool of patients efficiently and reliably. However, neurosurgical accreditation for robotic procedures is required. Consequently, compliance with standards and ethical considerations such as patient experience, marketing of the robotic surgery systems, cost-effectiveness, the privacy of patient data during remote operations, and responsibility for errors should also be seriously considered.

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