


GUIDELINE

Guideline for Posterior Atlantoaxial Internal Fixation Assisted by Orthopaedic Surgical Robot

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Atlantoaxial transarticular facet screw fixation (Magerl technique) and C₁ lateral mass screws combined with C₂ pedicle screws fixation (Harms technique) are the most commonly used techniques for posterior internal fixation in the upper cervical spine. Upper cervical spinal surgery is a technically demanding and challenging procedure because of complicated anatomical structures and frequent occurrence of anomalies. Accurate insertion of screws allows for stable and secure internal fixation, which is necessary for both techniques. Traditional methods under fluoroscopic assistance in this region cannot meet the requirements of high levels of accuracy and security during the procedure. Robot-assisted spinal surgery can provide accurate and reliable guidance during the screw insertion, which is evidenced in the literature. As a recently developed technique, robot-assisted surgery is supposed to be performed by skilled surgeons who have received standard training for robotic surgery. The standardized upper cervical spinal surgery assisted by the robot system needs to be introduced to these surgeons. Based on the consensus of consultant specialists, the literature review, and our local experience, this guideline included the introduction of the robotic system, the workflow of robot-assisted procedures, and the precautions to take during procedures. This guideline aims to provide a standardization of the robotic surgery for posterior atlantoaxial internal fixation.

Key words: Accuracy; Harms; Magerl; Robot-assisted surgery; Upper cervical spine

Introduction

The atlantoaxial joint acts as a highly mobile hinge joint at the craniocervical junction. Atlantoaxial deformity usually causes serious bulbomedullary compressive lesions, which mainly results from upper cervical spinal instability and manifests as spinal cord dysfunction. Internal fixation is the mainstay treatment for atlantoaxial instability^{1,2}. The initial method for atlantoaxial fixation was using steel wire and laminar clamps; however, it cannot provide enough strength; even with external fixation, the atlantoaxial fixation failure rate was still high³⁻⁵. As the fixation technique has developed over the past few decades, the instrumentation for atlantoaxial fixation has been greatly updated, and several types of fixation methods have been reported and applied in surgery^{6,7}. The most commonly used methods for atlantoaxial fixation were atlantoaxial transarticular facet screws (Magerl

technique)^{8,9} or atlantal lateral mass screws combined with axial pedicle screws (Harms technique)^{10,11}. Both methods can provide rigid fixation and have a high fusion rate.

The craniocervical junction comprises complicated anatomical structures, including the atlantoaxial joint, adjacent ligaments, vertebral arteries, and the spinal cord¹². To make it worse, deformities over the upper cervical spine have aberrant anatomy of both the cervical vertebra structure and the vertebral artery route in individuals¹³⁻¹⁶. As a result, the screw placement is a highly risky procedure, which may result in screw perforations and high vertebral artery injury rate^{17,18}. The internal fixation in the settings of atlantoaxial instability is regarded as challenging, especially in patients with craniocervical anomalies¹⁹.

Traditional posterior screw insertion for atlantoaxial fixation requires extensive exposure during surgery to

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distinguish the anatomical marks, and the C-arm X-ray machine is repeatedly used to confirm the position of screws. Nowadays, with the development of the concept of “precision medicine”, computer-assisted navigation systems and surgical robotics have been developed and widely applied in clinical practice. Many studies have demonstrated that application of a real-time 3D navigation system in surgery will significantly improve the accuracy of screw placement, and reduce intraoperative blood loss and the intraoperative radiation dose compared with the traditional freehand surgical method, especially in atlantoaxial fixation surgery^{20–22}. With intelligent operation planning, virtual simulation, real-time 3D image guidance, and accurate and stable robot arm operation, the orthopaedic robot system can also achieve precise screw insertion in minimally invasive surgery. Compared with other surgical assistive technology, robot-assisted spinal surgery is reported to have better results in terms of improving the precision of screw placement, reducing intraoperative radiation, and reducing surgical bleeding^{23,24}.

Based on review of the literature on orthopaedic robot systems that are used in spinal surgery, the TianJi Robot (developed by Beijing Jishuitan Hospital and Beijing Tinavi Technology) is the only robot that can be used for posterior screw insertion in the craniocervical area^{25–27}.

Specific robot-assisted surgical procedures and operative precautions for posterior atlantoaxial transarticular screw fixation (Magerl technique) and C₁ lateral screw together with C₂ pedicle screw fixation (Harms technique) are described below.

Orthopaedic Surgical Robot

An orthopaedic surgical robotic system mainly uses preoperative or intraoperative images for surgical planning, providing accurate positioning of surgical tools or implants through robotic arm movement and rigid guidance, assisting the surgeon to complete surgical operations. The work process mainly includes four steps: (i) surgical planning, where the surgeon carries out the surgical planning and selects suitable implants on the patient images using the device software; (ii) spatial registration, involving obtaining the spatial coordinates of the surgical trajectories via patent algorithm and tools; (iii) trajectory positioning, where the robotic arm automates movement by holding the surgical instruments to the desire position according to the spatial coordinates of the surgical trajectory; and (iv) assisted surgery, where the surgeon performs the surgical operation under the guidance of the robotic arm.

The orthopaedic surgical robotic system is composed of multiple sets of equipment, and its work steps involve images and optical data acquisition, spatial registration and image fusion, surgical planning, and mechanical positioning. To avoid ambiguity and standardize the work steps, this study will define the hardware equipment, the operation steps, and the concepts related to the orthopaedic surgical robotic system. The principles and equipment are illustrated below (Fig. 1).

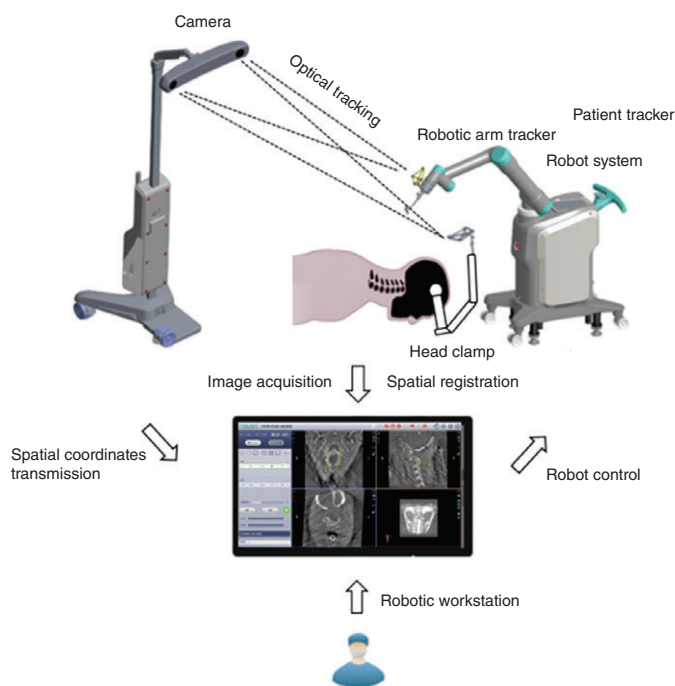


Fig. 1 The working principles of the TianJi Robot system.

Computer-Assisted Navigation Technique

A surgical assisted technique that combines modern computer, stereotactic, and medical imaging, to guide the surgeons for precise surgical planning and operation.

Orthopaedic Surgical Robotic Technique

A surgical assisted technique that combines computer-assisted navigation and surgical robotics, to guide the surgeons for precise surgical planning and operation.

Patient Tracker

A tracker connected to the patient’s anatomy during surgery to reflect or emit infrared light to the optical tracking camera.

Robotic Arm

A mechanism having two or more degrees of freedom, a certain degree of autonomy, and that is capable of automatically performing a predetermined task according to human instructions.

Robotic Arm Tracker

A tracker connected to the robotic arm during surgery to reflect or emit infrared light to the optical tracking camera.

Camera

The main component of the optical tracking system, a mechanical device for spatial positioning and tracking.

Guider

A navigation surgical tool that is attached to the end of the robot arm for positioning the surgical trajectory and has a quick connection interface to the base.

Registration

A mechanical device for spatial coordinate mapping and calibration.

Robotic Workstation

The robotic workstation holds the navigation computer system, the surgical planning software, and the robot operation software.

Positioning

The process of moving the robotic arm and guider to the planned trajectory position.

Target Audience

All personnel who participate in orthopaedic robot-assisted spinal surgery, which includes spine surgeons, nurses and engineers, are the target audience of this operative guideline. Manipulation of the surgical procedure and relative machine or mechanical devices should follow the standardized operative process recommended by the guideline. Proceed with precaution and consider the factors that could influence robotic navigation accuracy and endanger the patient's safety.

Indications and Contraindications

Indications

Indications for treatment include: instability of the atlantoaxial joint caused by various pathogenesis with or without bulbomedullary compression; spinal anomalies atlas dysplasia (e.g. occipitalization of the atlas), axis dysplasia (e.g. os odontoid), basilar invagination, and Klippel Feil syndrome; spinal trauma, including odontoid fracture and transverse ligament injury; and autoimmune disease and tumors (rheumatoid arthritis and tumors compromising the atlantoaxial joint stability).

Contraindications

Contraindications include: systematic diseases, such as severe hemorrhagic disease, respiratory function failure, and other diseases that contraindicate general anesthesia or a major surgery; patient position requirement cannot be satisfied; patient cannot tolerate radiation exposure; tracker position cannot meet the needs of accurate navigation; and a qualified navigation image cannot be obtained.

Robot-Assisted Procedures

Patient Preparation

After general anesthesia, patient positioning is the same as the requirements for traditional procedures: place the patient

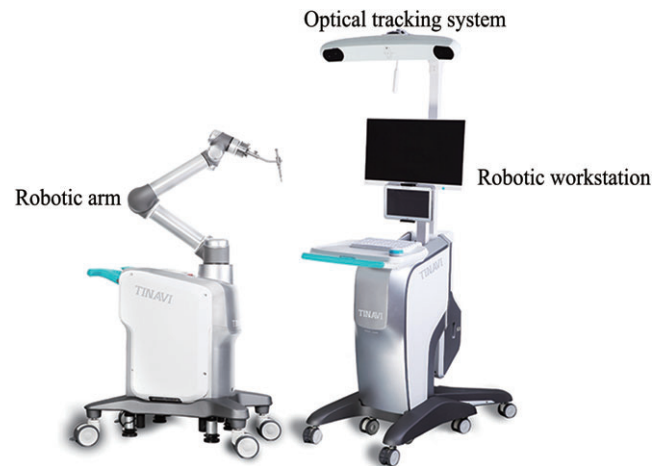


Fig. 2 TianJi Robot system.

in a prone position and fix the head onto the operating table using the Mayfield frame. If Magerl's procedure is performed and preoperative C_{1,2} dislocation exists, C_{1,2} reduction should be attempted by adjusting the position of the frame, which is monitored under fluoroscopy. If the C_{1,2} fusion is performed with autogenous iliac bone grafting, bone grafting is suggested to be performed prior to the C_{1,2} procedure.

During prepping and draping, an anchoring site for the patient tracker should be prepped and exposed. In open surgery, exposure is extended for anchoring the patient tracker. In percutaneous minimally invasive surgery, the patient tracker should be anchored at first and subsequently the stab wounds are created under robotic guidance.

Robotic Equipment Preparation

The TianJi Robot system consists of a robotic arm, an optical tracking system, a robotic workstation, and a navigation toolkit. The TianJi Robot system and the components around the robotic arm are shown in Figs. 2 and 3. All the relevant equipment is recommended to be arranged as follows in the operating room (Fig. 4).

Posterior Atlantoaxial Transarticular Screw Internal Fixation (Magerl Technique)

1. The patient tracker is commonly anchored onto the adjacent vertebral spinous process. The clamp connecting the patient tracker to the spinous process should be tightened and then the patient tracker is switched on (during open surgery: anchor the patient tracker onto the C₃ or C₄ spinous process; during percutaneous surgery: anchor the patient tracer onto the Mayfield frame). If posterior sublaminar wire fixation (Brooks technique) is performed at the same setting, the titanium cable is passed beneath the C₁ and C₂ lamina. Tighten the titanium cable, and the temporary clamp is used to fasten the titanium cable.
2. Adjust the position of the camera towards the operation space and the patient tracker.



Fig. 3 TianJi Robot navigation and positioning tools installation, including fixed ring, tracker, tool guider, lock screw, and holder base.

3. Install the registration and place it into the operating area so that the registration is within the fluoroscopy field.
4. Image acquisition: Perform 3D image scanning and complete the registration and spatial registration.
5. Designing and planning: Plan bilateral Magerl screws' parameters (diameter, length) in the robotic workstation. The screw entry point and the direction are designed based on the 3D images.
6. After the screw guider is installed, move the guider to the surgical field. The positioning accuracy will be displayed in the software interface in real time during the movement of the robot arm. Note: (i) If you find that the robot arm may touch the patient or surrounding obstacles, immediately press the emergency stop button; and (ii) the guider should be as close as possible to the operating area.
7. Sleeve installation: Place the sleeve into the screw guider. For percutaneous minimally invasive surgery, stab

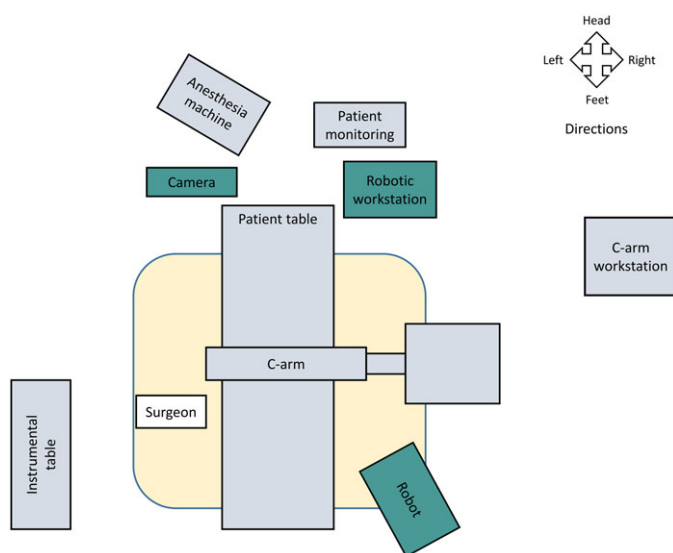


Fig. 4 Schematic diagram of operation room. When performing robotic surgery, it is recommended that the operation room be arranged as shown.

wounds can be made according to the position of the sleeve in contact with the skin. For open surgery, the sleeve is brought to the cortical bone surface after the bony surface is exposed.

8. Screw placement: The K-wire was drilled into the vertebrae, and then the optimal position is verified by fluoroscopy. If it is a cannulated screw, it can be instrumented directly along the K-wire; if it is a conventional screw, use the cannulated tap to prepare the trajectory first, and then insert the screw.
9. Remaining procedures: After the instrumentation is completed, verify the screw position by fluoroscopy. If the bone graft fusion is planned, complete corresponding operations.

C₁ Lateral Mass Screw and C₂ Pedicle Screw Internal Fixation (Harms Technique)

1. The patient tracker is commonly anchored onto the adjacent vertebral spinous process. The clamp connecting the patient tracker to the spinous process should be tightened and then the patient tracker is switched on (during open surgery: anchor the patient tracker onto the C₃ or C₄ spinous process; during percutaneous surgery: anchor the patient tracer onto the Mayfield frame).
2. Same as step (2) of Magerl technique.
3. Same as step (3) of Magerl technique.
4. Same as step (4) of Magerl technique.
5. Designing and planning: plan bilateral C₁ lateral mass screw and C₂ pedicle screw parameters (diameter, length) in the robotic workstation. The screw entry point and the direction are designed based on the 3D images.
6. Same as step (6) of Magerl technique.
7. Same as step (7) of Magerl technique.
8. Screw placement: The K-wire is drilled into the vertebrae, and then the optimal position is verified by fluoroscopy. If it is a cannulated screw, it can be instrumented directly along the K-wire; if it is a conventional screw, use the cannulated tap to prepare the trajectory first, and then insert the screw.
9. Remaining procedures: after the instrumentation is completed, verify the screw position by fluoroscopy. If the reduction is satisfactory, install the connecting rod and pre-tighten the screw heads; if the repositioning is unsatisfactory, then further adjustment is needed for atlantoaxial alignment or the curvature of the connecting rod until the reduction is satisfactory. If the bone graft fusion is planned, complete the corresponding operation (Fig. 5).

Precautions

Robot-assisted orthopaedic technology is a complex system based on advanced technologies such as image registration and fusion, robotics and automation technology, and precise equipment manufacturing. Its accuracy depends on these components of systems working properly; thus, it is

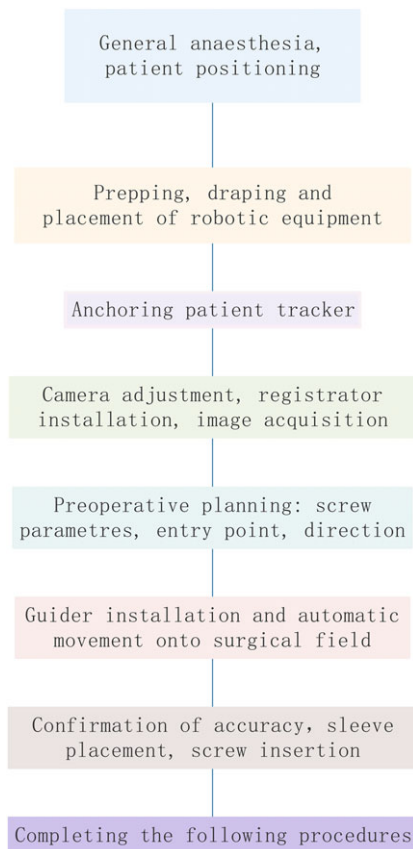


Fig. 5 Workflow of robot-assisted procedures.

affected by many factors. Common factors causing errors and strategies dealing with common errors are listed below.

Personnel Requirements

Doctors should have conventional surgical experience, relevant anatomical knowledge to determine whether the navigation system is accurate or not, and the ability to switch to conventional surgery when the robotic system fails to operate.

Environmental and Equipment Requirements

The operating room should have an appropriate area, with a good grounding system and power supply. The operating table should be radiolucent, avoiding metal artifacts that may affect the fluoroscopic process. The operating table base should not obstruct the intraoperative fluoroscopic machine obtaining intraoperative images. The operating environment should meet the normal working requirements according to the robot manual (including ambient temperature, humidity, air pressure, and voltage).

The preoperative navigation kit should be sterilized and placed on the operating table. The camera is placed on one side of the operating bed, above and facing towards the field, and cannot be blocked by the tray or the head frame. The C-arm machine is moved from one side of the operating

bed when it is used and is suggested to have a ground mark to guide the position properly. The main control trolley and the C-arm should be far from the operating area to facilitate the technician's operation.

Image Acquisition Requirements

The fluoroscopic images should demonstrate all the bony structures of key anatomical regions. The registration is clearly shown in the fluoroscopic field and the camera could simultaneously recognize and capture the spatial position information of the patient tracker and the robot arm tracker.

Tracker Placement Requirements

The tracker should be placed according to the operation and the patient's condition. When placing an external tracker, it should be firmly anchoring on the free arm, and the free arm should be firmly anchored onto the Mayfield head frame to avoid errors.

Navigational Deviation: Image Drift

The spatial position of the anatomy at the surgical site is required to be relatively fixed after the images are acquired. Any factors causing the image deviations between the guided position and the real position are regarded as image drift. The doctor should have the ability to determine if the navigation image is drifting. When image drift is suspected, select obvious anatomical landmarks, such as apex of spinous process, facet joints or transverse roots for verification. If the positioning is accurate, continue the surgery; however, if it is uncorrectable drift, rescanning is necessary. Common reasons for image drift include the following items, which need to be noted.

Relative Displacement of the Anatomical Structures and the Patient Tracker

1. Due to the large degree of motion of the upper cervical vertebrae, if the surgeon is excessively pulling the soft tissue, it will cause a large relative displacement between the bony structures. Therefore, the intraoperative manipulation needs to be gentle, and the positioning accuracy should be noted during the manipulation.
2. Decompression or osteotomy will destroy the stability of the spine, resulting in relative displacement between the anatomical structures. If intraoperative conditions permit, the procedure of fixation is advised to be performed first and followed by the remaining procedures to avoid image drift. If the accuracy is still uncertain, the doctor should select the anatomical landmark for verification.
3. If the patient's position changes, it may cause the changing of the spatial position of the patient's anatomical structures, and image acquisition and surgical planning should be re-executed.

Patient Tracker Loosening

The patient tracker needs to be firmly anchored to the patient's anatomy. If the intraoperative tool or the surgeon

accidentally moves or touches the tracker, or the tracker is pulled by the skin during minimally invasive surgery, the position of the tracker would be changed. That will lead to a decrease in positioning accuracy or a failure in positioning. In this situation, image acquisition and surgical planning should be repeated.

Misalignment Caused by Lighting Problems

The robot system must maintain good reflection and reception of infrared light. If the angle or distance exceeds the receiving range, or other light interference, it may cause misalignment. The camera should be adjusted so that the surgical field is in the center of its detection range. Since the tracker reflects the light to the camera, strong direct light and blood staining on the reflection ball of the tracker may interfere the reflection and reception process of infrared light. Thus, strong direct light or blood staining on the tracker should be avoided.

Regular Maintenance of Robot Equipment

1. Data cable: Check whether the transmission data line interface is loosening or disconnected. If the data cable is aging, it needs to be replaced.
2. Robotic tools: Before the operation, the robot tool should be carefully checked for metal fatigue to prevent the tool from breaking during the operation.
3. System accuracy: Accuracy calibration should be performed periodically.

Others

The upper cervical vertebra has a high degree of movement, which requires a careful and experienced surgeon. If the

robotic arm is found to be unable to reach the designated position due to the surrounding environment during the operation, the surgical path should be adjusted. If there is a sudden power failure of the robot system, the system should be restarted: If only the mechanical system of the mechanical arm is powered off, it is generally unnecessary to reacquire images and redo the surgical planning, but if the overall system of the robot is powered off, the image acquisition and surgical planning should be repeated.

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List of Names of Consultant Specialists

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