Original Article

Solid and hollow pedicle screws affect the electrical resistance: A potential source of error with stimulus-evoked electromyography

Hongwei Wang, Xinhua Liao[1], Xianguang Ma[1], Changqing Li, Jianda Han[2], Yue Zhou

Abstract

Background: Although stimulus evoked electromyography (EMG) is commonly used to confirm the accuracy of pedicle screw placement. There are no studies to differentiate between solid screws and hollow screws to the electrical resistance of pedicle screws. We speculate that the electrical resistance of the solid and hollow pedicle screws may be different and then a potential source of error with stimulus-evoked EMG may happen.

Materials and Methods: Resistance measurements were obtained from 12 pedicle screw varieties (6 screws of each manufacturer) across the screw shank based on known constant current and measured voltage. The voltage was measured 5 times at each site.

Results: Resistance of all solid screws ranged from 0.084 Ω to 0.151 Ω (mean =0.118 ± 0.024 Ω) and hollow screws ranged from 0.148 Ω to 0.402 Ω (mean = 0.285 ± 0.081 Ω). There was a significant difference of resistance between the solid screws and hollow screws ($P < 0.05$). The screw with the largest diameter no matter solid screws or hollow screws had lower resistance than screws with other diameters. No matter in solid screws group or hollow screws group, there were significant differences ($P < 0.05$) between the 5.0 mm screws and 6.0 mm screws, 6.0 mm screws and 7.0 mm screws, 5.0 mm screws and 7.0 mm screws, 4.5 mm screws and 5.5 mm screws, 5.5 mm screws and 6.5 mm screws, 4.5 mm screws and 6.5 mm screws. The resistance of hollow screws was much larger than the solid screws in the same diameter group ($P < 0.05$).

Conclusions: Hollow pedicle screws have the potential for high electrical resistance compared to the solid pedicle screws and therefore may affect the EMG response during stimulus-evoked EMG testing in pedicle screw fixation especially in minimally invasive percutaneous pedical screw fixation surgery.

Key words: Electrical resistance, electromyography, pedicle screw, percutaneous pedicle screw

Introduction

Pedicle screw fixation has become the definitive procedure for spinal instrumentation. The reported incidence of malpositioned pedicle screws in both cadaveric studies and clinical series has ranged from about 5% to as much as 40%, with potential consequences of construct failure, visceral injury, or neurologic injury.[1-8] In traditional open instrumentation procedures, pedicle screws are placed free hand with the use of anatomic markers.[9,10] The significant individual patient variation of pedicle anatomy can lead to difficulties in accurately placing pedicle screws.[11] Bony landmark deformities hamper the ability to obtain reliable fluoroscopic images. Furthermore, surgeons and operating room personnel are subjected to varying degrees of radiation when we use intraoperative fluoroscopy.[12] Recently, computer navigation has been reported to be more accurate, but this modality is time consuming, may lead to excessive radiation exposure and is not available in every institution because of its expense. Electrophysiological methods using intraoperative real-time electromyography (EMG) recordings differ from the other modalities in that they provide functional data regarding the nerve roots, which are close to the pedicle screws.

In addition to advances in intraoperative monitoring, minimally invasive techniques have found increasing application in spinal surgery. Pedicle screws have

Department of Orthopaedics, Xinqiao Hospital, Chongqing, [1]Department of Physics, College of Medicine, Third Military Medical University, Chongqing, [2]State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Science, Shenyang, China

Address for correspondence: Dr. Yue Zhou, Department of Orthopedics, Xinqiao Hospital, Third Military Medical University, Chongqing - 400 037, PR. China. E-mail: zhouyue_xinqiao@163.com

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been successfully placed by a variety of percutaneous techniques.[13,14] The risks in percutaneous pedicle screw placement are theoretically greater than open screw placement because of complete lack of direct visualization of landmarks or palpation of the medial pedicle and complete reliance on radiographic guidance. For this reason, EMG testing may have even greater significance in percutaneous pedicle screw placement than open procedures. Stimulation thresholds have been shown to vary in the several studies. The strong likelihood of a pedicle wall defect and a potential screw contact with a nerve root and/or the dura ranged from 6 mA to 11 mA.[15-18] The electrical conductivity of pedicle screws may be one important variable that can affect the threshold. Different from solid pedicle screws mostly used in open surgery, pedicle screws used in minimally invasive surgery are mostly polyaxial hollow pedicle screws so that the pedicle screws can be inserted along the position and direction adjusted guiding needle. To our knowledge, no earlier study evaluated effects of the hollow or solid screw design on its intrinsic electrical properties. We have a hypothesis that the electrical resistance may be different between the solid and hollow pedicle screws, the difference may become a potential source of error with stimulus-evoked EMG. In order to test and verify the hypothesis, resistance measurements were obtained from 12 pedicle screw varieties (6 screws of each manufacturer) across the screw shank based on known constant current and measured voltage.

Materials and Methods

Twelve titanium alloy (Ti-6Al-4V) pedicle screws from two different manufacturers [Table 1] commonly used in spine surgery were clamped by two aluminium clamps to provide a connection with the current source. A current meter (HY1791-5S system direct current power supply, Huaian Yaguang Electronic Co, Jiangsu, China) was attached to the adjustable resistor with a current wire on each side and through a current wire to the pedicle screw. This created an electrical circuit [Figure 1]. Two voltage wires that measured a current potential were attached 20 mm apart along the length of a screw (the X1-X2 distance), using two aluminium clamps which has extremely low resistivity. A current (I) measured using a multimeter (UNI-T UT60A-CN digital multimeter, UNI-T technology Co, China) was passed through a screw via current wire. Generated voltage (V) was recorded using a voltmeter (UJ31 system direct current potentiometer, Hangzhou Jingke Electronic Co, Zhejiang, China). The resistance was calculated based on Ohm's law ($R = V/I$); where R is resistance of an object (measured in ohms; Ω), V is a potential difference across an object (measured in volts) and I is a current through an object (measured in amperes). Each screw was tested 5 times at respectively 50 mA, 100 mA, 150 mA, 200 mA and 250 mA to minimize a current selection bias error. Each screw had several diameters. Statistical analysis was carried out by using SPSS 15.0 (SPSS/PC, Chicago, IL, USA) software and ANOVA. As it is shown in Table 1, there are different categories of screw sizes from two different manufacturers: pedicle screws with diameter of 5.0 mm, 6.0 mm, 7.0 mm got from Johnson company (Manufacturer A) and pedicle screws with diameter of 4.5 mm, 5.5 mm, 6.5 mm got from Medtronic company (Manufacturer B).

Table 1: Screws used in the study

Screw manufacturer	Screw material	Screw design	Screw diameter (mm)
A	Titanium alloy	Solid screw	5.0, 6.0, 7.0
	Titanium alloy	Hollow screw	5.0, 6.0, 7.0
B	Titanium alloy	Solid screw	4.5, 5.5, 6.5
	Titanium alloy	Hollow screw	4.5, 5.5, 6.5

Results

The calculated resistance values for each screw are summarized in Tables 2 and 3. Resistance of all solid screws ranged from 0.084 Ω to 0.151 Ω (mean = 0.118 ± 0.024 Ω) and hollow screws ranged from 0.148 Ω to 0.402 Ω (mean = 0.285 ± 0.081 Ω), there was a significant difference between the solid screws and hollow screws ($P < 0.05$). Larger diameter screw had lower resistance than other diameter screws in solid screws or hollow screws group. No matter in solid screws group or hollow screws group, there were significant differences ($P < 0.05$) between the 5.0 screws and 6.0 screws, 6.0 screws and 7.0 screws, 5.0 screws and 7.0 screws, 4.5 screws and 5.5 screws, 5.5 screws and 6.5 screws, 4.5

Table 2: Calculated screw resistance values

Screw manufacturer	Test trial	A						B					
Screw design		Solid screw (Diameter in mm)			Hollow screw (Diameter in mm)			Solid screw (Diameter in mm)			Hollow screw (Diameter in mm)		
Diameter (mm)		5.0	6.0	7.0	5.0	6.0	7.0	4.5	5.5	6.5	4.5	5.5	6.5
Screw resistance (Ω)	1	0.150	0.124	0.097	0.293	0.239	0.149	0.147	0.119	0.089	0.402	0.352	0.294
	2	0.149	0.114	0.096	0.290	0.236	0.148	0.143	0.116	0.086	0.399	0.347	0.291
	3	0.151	0.123	0.095	0.290	0.236	0.148	0.138	0.109	0.086	0.398	0.344	0.289
	4	0.148	0.123	0.095	0.293	0.236	0.148	0.141	0.105	0.086	0.397	0.345	0.289
	5	0.148	0.123	0.095	0.291	0.236	0.148	0.141	0.103	0.084	0.395	0.345	0.287

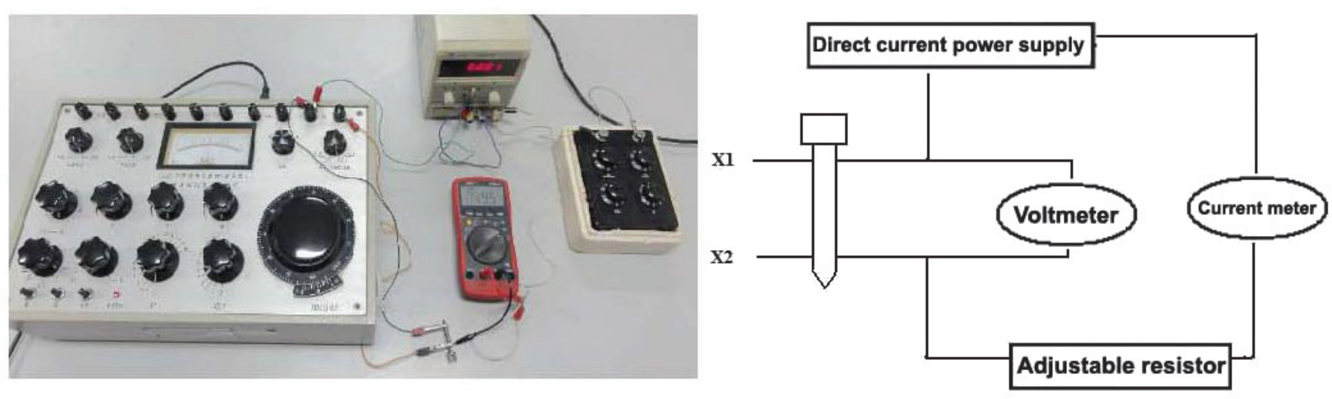

Figure 1: The electrical circuit used in this study

Table 3: Mean pedicle screw resistance

Screw manufacturer	Diameter (mm)	Solid screw (Ω)	Hollow screw (Ω)	*P*
A	5.0	0.149±0.001	0.291±0.001	0.000
	6.0	0.123±0.004	0.237±0.001	0.000
	7.0	0.095±0.001	0.148±0.001	0.000
B	4.5	0.142±0.003	0.398±0.002	0.000
	5.5	0.110±0.007	0.347±0.003	0.000
	6.5	0.086±0.002	0.290±0.003	0.000

screws and 6.5 screws. Resistance of all hollow screws was significantly larger than the solid screws with the same diameter ($P < 0.05$).

Discussion

To prevent nerve root injury, investigators have sought ways to ensure that pedicle screws are confined within the bony cortex of the pedicle. In 1991, Calancie *et al*. introduced intraoperative evoked EMG recordings in a porcine model.[19] The technique offered an objective means of evaluating pedicle screw placement. By applying an electrical stimulus through the pedicle screw, then recording the resulting evoked EMG response, threshold values can help determine medially malpositioned screws. Now, the intraoperative electrical testing of pedicle screws is a widely accepted technique of minimizing intraoperative nerve root irritation or an injury during the insertion of spinal instrumentation.[15-18] EMG pedicle screw testing works by stimulating the placed screw and depending on the threshold needed to elicit a compound muscle action potential (CMAP) from the corresponding myotome, an indication of pedicle breach can be determined. As the pedicle acts as an insulator, the higher the response threshold, the decreased likelihood of direct or near contact to the exiting nerve root.

On the other hand, stimulation thresholds have been shown to vary in several studies. The strong likelihood of a pedicle wall defect and a potential screw contact with a nerve root and/or the dura ranged from 6 mA to 11 mA.[15-18] The electrical conductivity of pedicle screws may be an important variable that can affect the threshold.[20] Different from solid pedicle screws mostly used in open surgery, pedicle screws used in minimally invasive surgery are mostly polyaxial hollow pedicle screws so that the pedicle screws can be inserted along the position and direction adjusted guiding needle. To our knowledge, no earlier study evaluated effects of the hollow or solid screw design on its intrinsic electrical properties.

The current study showed that larger diameter screws from the same manufacture had lower resistance and more current flowed through it. The results are consistent with a previous study.[20] Anderson *et al*.[21] demonstrated that polyaxial pedicle screws have the potential for high electrical resistance between the mobile crown and shank and therefore may fail to demonstrate an EMG response during stimulus-evoked EMG testing in the setting of a pedicle breach. Furthermore, Limthongkul *et al*.[20] found there were no difference between different probe locations (outer and inner mobile crown versus a screw's shank stimulation) and voltage through a screw. A probable reason for that is that the equipment used in the study completed by Limthongkul *et al*. was more accurate.

Our study confirmed that resistance of pedicle screws with a larger diameter was lower. The measured screw resistances of hollow pedicle screws were larger than that of solid pedicle screws. By using a larger screw or solid pedicle screw higher electrical current passes through it which might stimulate a nerve root earlier. Therefore, if higher threshold values are used intraoperatively, there could be a higher incidence of false positive measurements if larger diameter screws or solid screw are used. A surgeon might accept even a lower threshold levels as a sign of an intact pedicle during the spinal cord stimulation. Therefore, in a large diameter screws or solid screws even lower threshold might not necessary indicate screw perforation through the pedicle cortex and a possible nerve root injury.

Ozgur *et al.*[22] pointed out that tapping often improved thresholds in EMG testing to identify suboptimal screw trajectories in minimally invasive pedicle screw fixation, perhaps by compressing the bone and creating a denser, more insulative pedicle wall. Other potential pitfalls in neuromonitoring may be caused by an actual condition of a nerve root. Limbrick and Wright[23] showed that significantly higher stimulus intensities were required to evoke myogenic responses from chronically compressed nerve roots compared with normal nerve roots. There were many studies about the utility of EMG testing in percutaneous pedicle screw fixation techniques.[22,24,25] Ozgur *et al.*[22] used the initial fluoroscopically guided k-wires and the subsequent taps were insulated and stimulated via an automated EMG system, then pointed out that EMG testing helps to identify suboptimal screw trajectories, allowing for early adjustment and confirmation of improved placement. Bindal and Ghosh[24] pointed out that a continuous stimulation pedicle access needle alerts the surgeon to incorrect medial trajectories and may lead to safer pedicle cannulation. Wood and Mannion[25] pointed out that the combination of computer-assisted navigation combined with continuous EMG monitoring during pedicle cannulation results in a low rate of pedicle screw misplacement. Furthermore, this technique allows reduction of the radiation exposure for the surgical team without compromising the accuracy of screw placement. Through these techniques, we can see that the interference of screws can be avoided.

This study has some limitations. It mainly focuses on the electrical resistance testing of the pedicle screws and discussion about the influence of pedicle screws to the stimulus-evoked EMG. Other parameters with higher resistance that can interfere with an intraoperative spinal cord monitoring *in vivo* such as: pedicle cortical thickness, conditions of a recording nerve, conductivity of a muscle and thickness of a subcutaneous fat layer when using percutaneous CMAP recording; however, these factors were not examined in this study.

The question of clinical relevance of our data remains open and further research on this is needed. Based on the prospective clinical series some authors recommended that the pedicle tap nerve root stimulation threshold stimulus intensity below 12 mA or 15 mA is to be considered an indicator for a potential pedicle wall defect due to screw perforation and a possible contact of a screw with a nerve root.[24,26] The EMG continuously stimulus intensity is set at 5 mA or 7 mA stimulus to monitor the lumbar nerve roots at the operated levels through the pedicle access needle.[24,25] The stimulation threshold stimulus intensities are not absolute when we use different stimulators such as pedicle tap and pedicle access needle with different intrinsic properties.[24-26] So we speculate that the difference of electrical resistance between the solid and hollow pedicle screws may become a potential source of error with stimulus-evoked EMG. To avoid false-negative stimulus-evoked EMG testing through the different design of pedicle screws such as solid or hollow pedicle, the cathode stimulator probe should be applied to the pedicle access needle or pedicle tap with constant structure especially in the minimally invasive surgery, the technique may allow us the early adjustment and confirmation of improved pedicle screw placement trajectory. Through the technique, we can see that the interference of screws can be avoided. But the set of stimulation threshold need further investigation, future research should also look into other factors that might affect threshold stimulus intensity such as thickness and resistance of a pedicle cortex around the pedicle access needle or pedicle tap.

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