

Original Article

A novel probe for measuring tissue bioelectrical impedance to enhance pedicle screw placement in spinal surgery

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Abstract: Posterior spinal reconstruction with rods and pedicle screws has been widely used to corrects coliosis and other forms of degenerative spinal deformities. However, insertion of pedicle screws is often clinically challenging, particularly in patients with severe deformity. Bioelectrical impedance analysis is a technique that exploits the electrical properties of biological organs and tissues to indicate their compositions. Bioelectrical impedance measurement is non-invasive, simple, with adequate repeatability, and at a relatively low cost. In our study, we designed a bioelectrical impedance pedicle probe and use it to determine the bioelectrical impedance values *in vitro* and *in vivo* of different tissues relevant to pedicle screw insertion. We measured the bioelectrical impedance of different tissues relevant to pedicle screw placement *in vitro* and *in vivo* and explored the use of a prototype bioelectrical impedance pedicle probe in guiding pedicle screw placement during spine surgery in animals. These data suggested that this novel bioelectrical impedance pedicle probe may be a new technique that has potential to offer accurate and safe placement of pedicle screws in spine surgery.

Keywords: Pedicle screws, severe spinal deformities, bioelectrical impedance, probe

Introduction

Posterior spinal reconstruction with rods and pedicle screws has been widely used to corrects coliosis and other forms of degenerative spinal deformities [1-5]. Suk and colleagues first described the use of thoracic pedicle screws in the treatment of scoliosis in 1995, in which these screws permitted three-dimensional correction of deformity [6]. However, insertion of pedicle screws is often clinically challenging, particularly in patients with severe deformity, owing to the narrow pedicle as well as anatomical variations in the orientation of the pedicle and its relationship to the adjacent spinal cord, nerve roots and vessels [7-10]. Each of these factors increases the risk of potentially disastrous neural and vascular injuries caused by misplacement of pedicle screws

[11, 12]. It is therefore important to establish a new method for guiding the placement of pedicle screws.

Bioelectrical impedance analysis is a technique that exploits the electrical properties of biological organs and tissues to indicate their compositions [13-15]. Bioelectrical impedance measurement is non-invasive, simple, highly repeatable and economical [16-18]. The utilization of bioelectrical impedance has been reported in different clinical settings [19-21]. In particular, this method has been extensively used in body composition appliance, impedance imaging, and blood flow imaging [22-24].

In this study, we measured the bioelectrical impedance *in vitro* and *in vivo* of different tissues relevant to pedicle screw placement and

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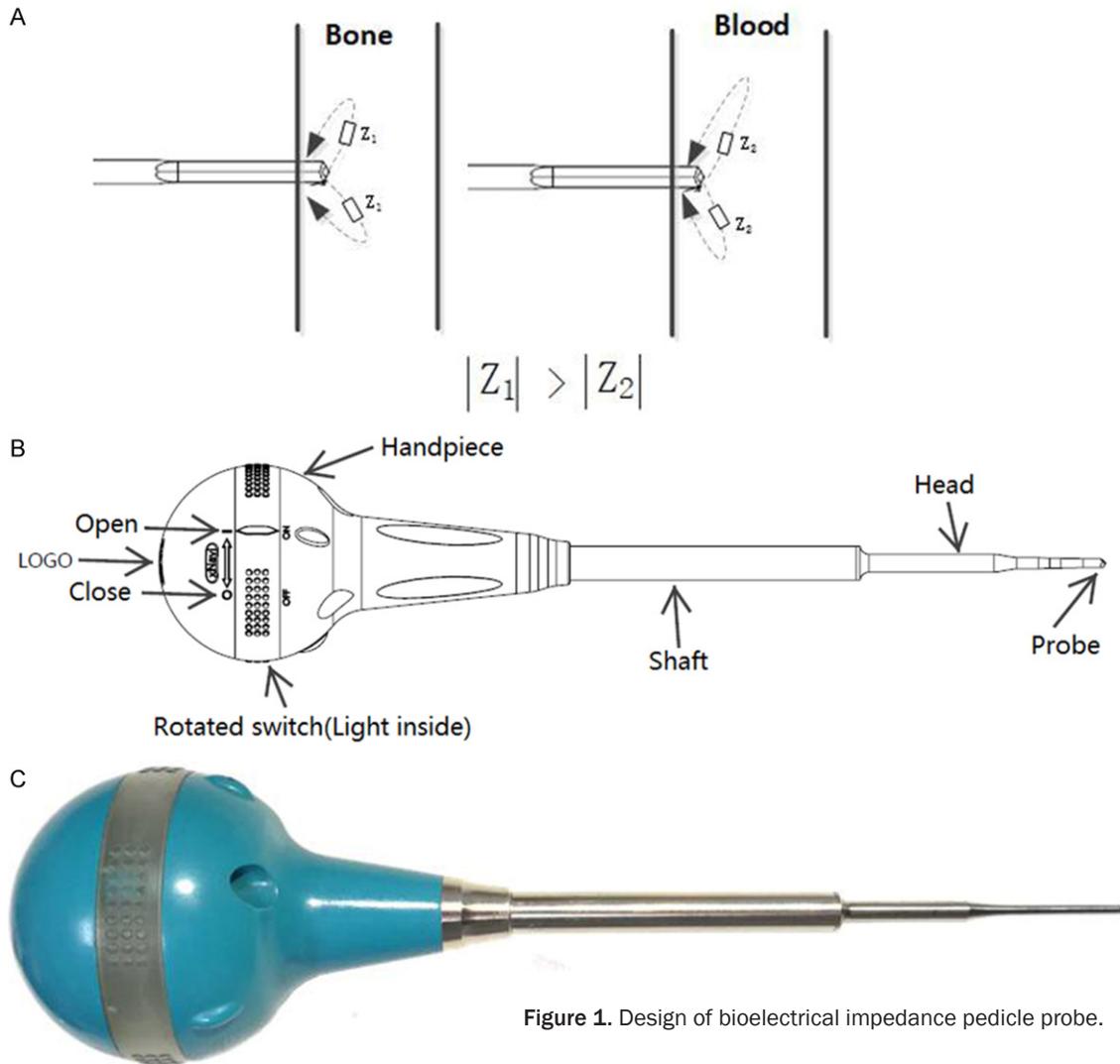


Figure 1. Design of bioelectrical impedance pedicle probe.

explored the use of a prototype bioelectrical impedance pedicle probe in guiding pedicle screw placement during spine surgery in swine.

Materials and methods

Animals

The animal study protocol was approved by the Ethics Committee of Peking Union Medical College Hospital. Four mature swine (age, 20 weeks; weight, 50-60 kg) were used in this study. We performed 20 pedicle screw insertions in each swine.

Design of bioelectrical impedance pedicle probe

This new bioelectrical impedance pedicle probe consisted of a bioelectrical impedance detec-

tor and a pedicle probe, which was invented by our research group (Patent no. ZL 20152010-4894.9) (**Figure 1**). This novel probe has three sizes, namely 2 mm, 3 mm and 4 mm in diameter, respectively.

Bioelectrical impedance measurements

The bioimpedance data of different tissues, including blood, fat, muscle, cortical bone and cancellous bone, were recorded *in vitro*. The signal of bioelectrical impedance was also recorded during the pedicle screw implantation *in vivo*.

Analysis of pedicle screw insertion

Pedicle screw insertion was performed guided by intra-operative X-ray imaging by surgeons who were not involved in the study.

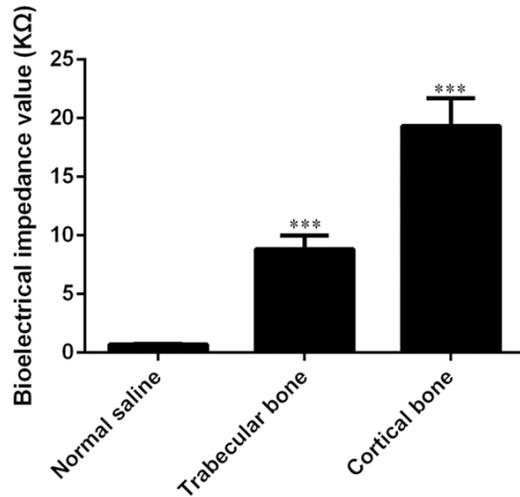


Figure 2. The bioelectrical impedance of normal saline, trabecular bone and cortical bone was shown. Difference between groups was measured by one-way ANOVA. *** $P < 0.001$ significantly different from normal saline.

Statistical analysis

Statistical analysis was performed using SPSS (version 18, Chicago, IL, USA). Data were shown as mean \pm standard deviation (S.D.). Difference among three or more groups was measured by one-way analysis of variance (ANOVA). Statistical significance was considered at $P < 0.05$.

Results

Bioelectrical impedance of different tissues in vitro and in vivo

We firstly measured the bioelectrical impedance of trabecular bone and cortical bone *in vitro* with normal saline as control. As shown in **Figure 2**, there were significant differences among the bioelectrical impedance of normal saline, trabecular bone and cortical bone. The bioelectrical impedance value of cortical bone was twice higher than that of trabecular bone and 20-fold higher than normal saline. In the next step, we measured the bioelectrical impedance values of blood, dura mater, trabecular bone and cortical bone *in vivo*. Consistent with *in-vitro* data, the bioelectrical impedance value of cortical bone was highest among the tested tissues, followed by trabecular bone, dura mater and blood. The bioelectrical impedance values of all tested tissues were stable

during repeated measurements over time (**Figure 3**).

Testing bioelectrical impedance pedicle probe during surgery in swine

Next, we validated the effectiveness of bioelectrical impedance probe in monitoring the path of a pedicle screw canal during spine surgery in swine. We firstly used this pedicle probe to create a correctly pathed pedicle screw canal. This bioelectrical impedance pedicle probe, which was used in the operation, was shown in **Figure 4A**. Anteroposterior (**Figure 4B**) and lateral (**Figure 4C**) radiographs confirmed that this pedicle screw insertion was properly done. The changes in bioelectrical impedance value during pedicle screw canal creation are shown in **Figure 4D**. Bioelectrical impedance measurements indicated that the pedicle probe passed through two tissues, namely blood and trabecular bone (**Figure 4D**). Then, we utilized this pedicle probe to create a pedicle screw canal with partial drilling of medial cortex. There were three tissues, namely blood, trabecular bone and cortical bone, which the pedicle probe passed through as reflected from the changes in bioelectrical impedance value (**Figure 5C**). The creation of a pedicle screw canal with partial drilling of medial cortex was confirmed by the anteroposterior (**Figure 5A**) and lateral radiographs (**Figure 5B**). Finally, we created a pedicle screw canal that passed through the spinal canal to mimic pedicle screw misplacement. The insertion of pedicle probe during the operation is shown in **Figure 6A**. The creation of an incorrect pedicle screw path was confirmed by anteroposterior (**Figure 6B**) and lateral (**Figure 6C**) radiographs. The changes in bioelectrical impedance value of the last procedure suggested that the probe had passed through four tissues, namely blood, trabecular bone, dura mater and cortical bone (**Figure 6D**).

Discussion

In the present study, we reported the performance of a new bioelectrical impedance pedicle probe and used it to measure the bioelectrical impedance values of normal saline, trabecular bone and cortical bone *in vitro*. Our data confirmed that there are significant differences among the bioelectrical impedance values of these samples. On this basis, we determined the bioelectrical impedance of blood,

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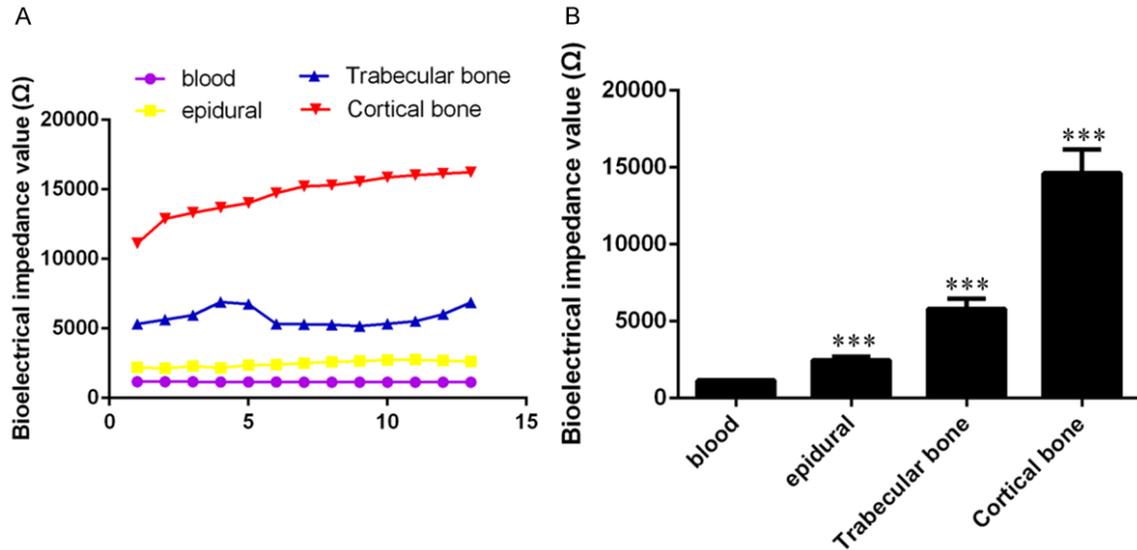


Figure 3. A. The bioelectrical impedance values of blood, dura mater, trabecular bone and cortical bone was determined *in vivo*. The x-axis indicated time. B. The bioelectrical impedance value of cortical bone was highest among the tested tissues, followed by trabecular bone, dura mater and blood. Difference between groups was measured by one-way ANOVA. *** $P < 0.001$ significantly different from blood.

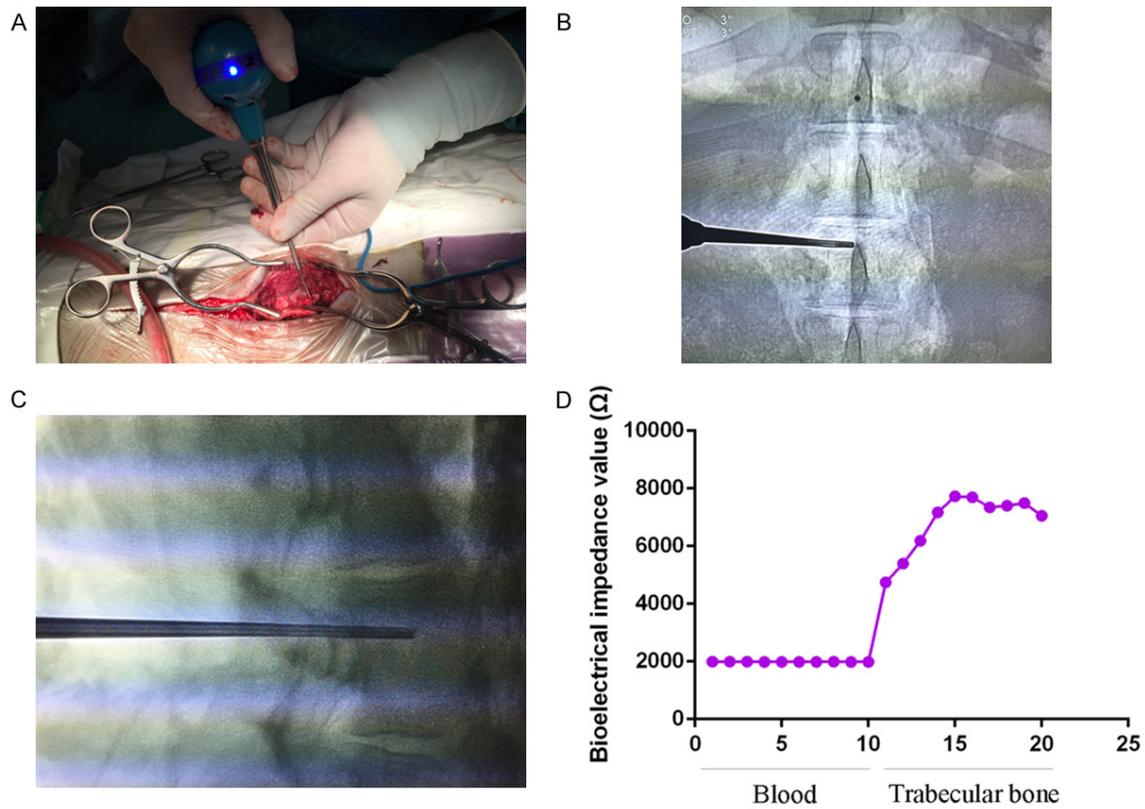


Figure 4. Testing bioelectrical impedance pedicle probe during surgery in swine. (A) This bioelectrical impedance pedicle probe, which was used in the operation. Anteroposterior (B) and lateral (C) radiographs confirmed that this pedicle screw insertion was properly done. (D) The changes in bioelectrical impedance value during pedicle screw canalcreation are shown. The x-axis indicated time.

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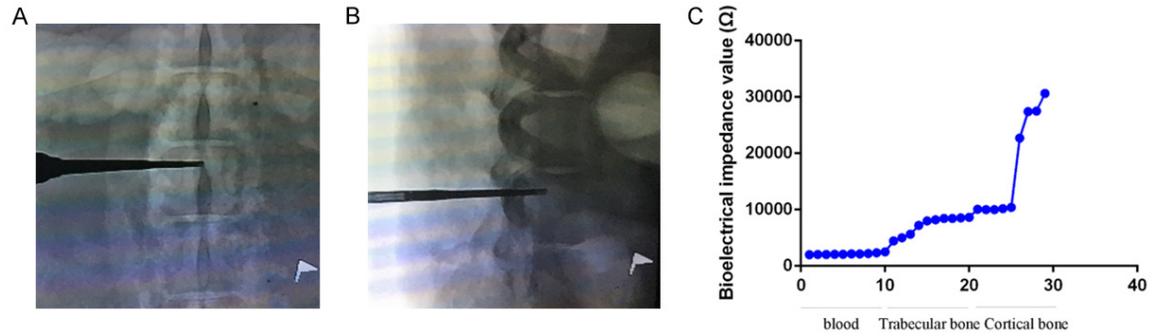


Figure 5. Utilization of pedicle probe to create a pedicle screw canal with partial drilling of medial cortex. The creation of a pedicle screw canal with partial drilling of medial cortex was confirmed by the anteroposterior (A) and lateral (B) radiographs. (C) There were three tissues, namely blood, trabecular bone and cortical bone, which the pedicle probe passed through as reflected from the changes in bioelectrical impedance value. The x-axis indicated time.

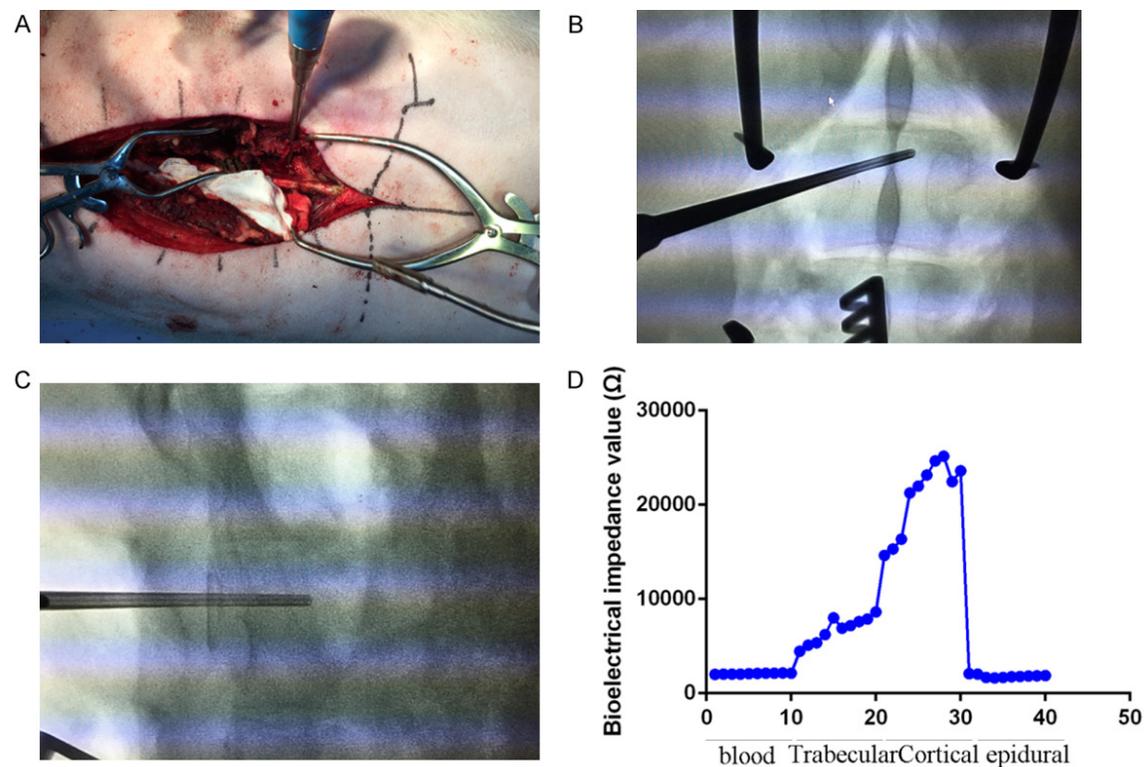


Figure 6. A pedicle screw canal that passed through the spinal canal to mimic pedicle screw misplacement. A. The insertion of pedicle probe during the operation is shown. B, C. The creation of an incorrect pedicle screw path was confirmed by anteroposterior and lateral radiographs. D. The changes in bioelectrical impedance value of the last procedure suggested that the probe had passed through four tissues, namely blood, trabecular bone, dura mater and cortical bone. The x-axis indicated time.

dura mater, trabecular bone and cortical bone *in vivo*. The bioelectrical impedance value of cortical bone was highest among these tissues. Moreover, we validated the effectiveness of our probe in creating and informing the path of pedicle screw canal during spine surgery in swine. We used this probe to create a correctly

pathed pedicle screw canal, a pedicle screw canal with partial drilling of medial cortex and a wrongly pathed pedicle screw canal that passed through spinal canal. The changes in bioelectrical impedance value correctly indicated the tissues through which the probe had passed through during these operations. These

data suggested that use of this bioelectrical impedance pedicle probe could be further assessed in human spine surgery in the future.

Posterior spinal fixation with pedicle screws is a gold-standard surgery for treatment of patients with scoliosis and other degenerative spine disorders [25, 26]. However, pedicles screw insertion can be technically challenging [27, 28]. It has been reported that the rate of pedicle screw misplacement with the freehand technique can range from 5% to 43% [29-31]. Therefore, approaches to enhance the accuracy and safety of pedicle screw placement in spine surgery have been studied in clinical and cadaveric studies. For instance, computer-assisted pedicle screw navigation technique has been shown to improve safety and accuracy and decrease the risk of blood vessel and spinal nerve damage [32, 33]. However, this method needs to involve surface registration of each vertebra, which lengthens operation time and raises the potential for registration-based errors. Moreover, this technique invokes higher cost and more man power during surgery and increases the risk of intraoperative infection. More importantly, the navigation technique is based on anatomical mapping. DeVito and colleagues reported their experience with SpineAssist robot in fourteen spine centers, suggesting a rate of 98% of acceptable screw insertion without occurrence of nerve injury [34]. However, it still has some shortcomings, such as higher cost and longer surgery duration. Therefore, it is useful to establish a new method for placing pedicle screws.

Bioelectrical impedance measurement is a new technique that exploits the electrical properties of biological tissues and organs to inform clinical decision [35-38]. For examples, Pan et al and colleagues used bioelectrical impedance measurement to determine the fat-free mass in acute spinal cord injury [39]. Hansen also reported the use of bioelectrical impedance for estimating postmortem interval [40]. In our study, we have applied this technique to spine surgery for pedicle screw insertion.

Several limitations of this study should be mentioned. First, we only used this bioelectrical impedance pedicle probe during surgery in swine. The clinical utility needs to be assessed in human in the future. Moreover, we only measured the bioelectrical impedance of blood, dura

mater, trabecular bone and cortical bone. The values for other tissues or fluids of relevance, such as the intervertebral disc, cerebrospinal fluid, spinal nerve and spinal cord, have not been determined. However, the direct penetrations into such tissues or fluids by pedicle screws during spinal surgery are rare. In addition, we only confirmed the orientation of pedicle screw canals with X-ray radiography. It should be ideally confirmed with computer tomography scanning. Finally, the use of bioelectrical impedance pedicle probe should be compared head-to-head with other methods, such as freehand technique and computer-assisted method.

In conclusion, we designed a bioelectrical impedance pedicle probe and use this probe to determine the bioelectrical impedance values *in vitro* and *in vivo* of different tissues relevant to pedicle screw insertion. We also validated the use of bioelectrical impedance pedicle probe for guiding the creation of pedicle screw canals during spine surgery in swine.

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Disclosure of conflict of interest

None.

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