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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 screwsis often clinically challenging, particularlyin 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 probein 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 indifferent 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

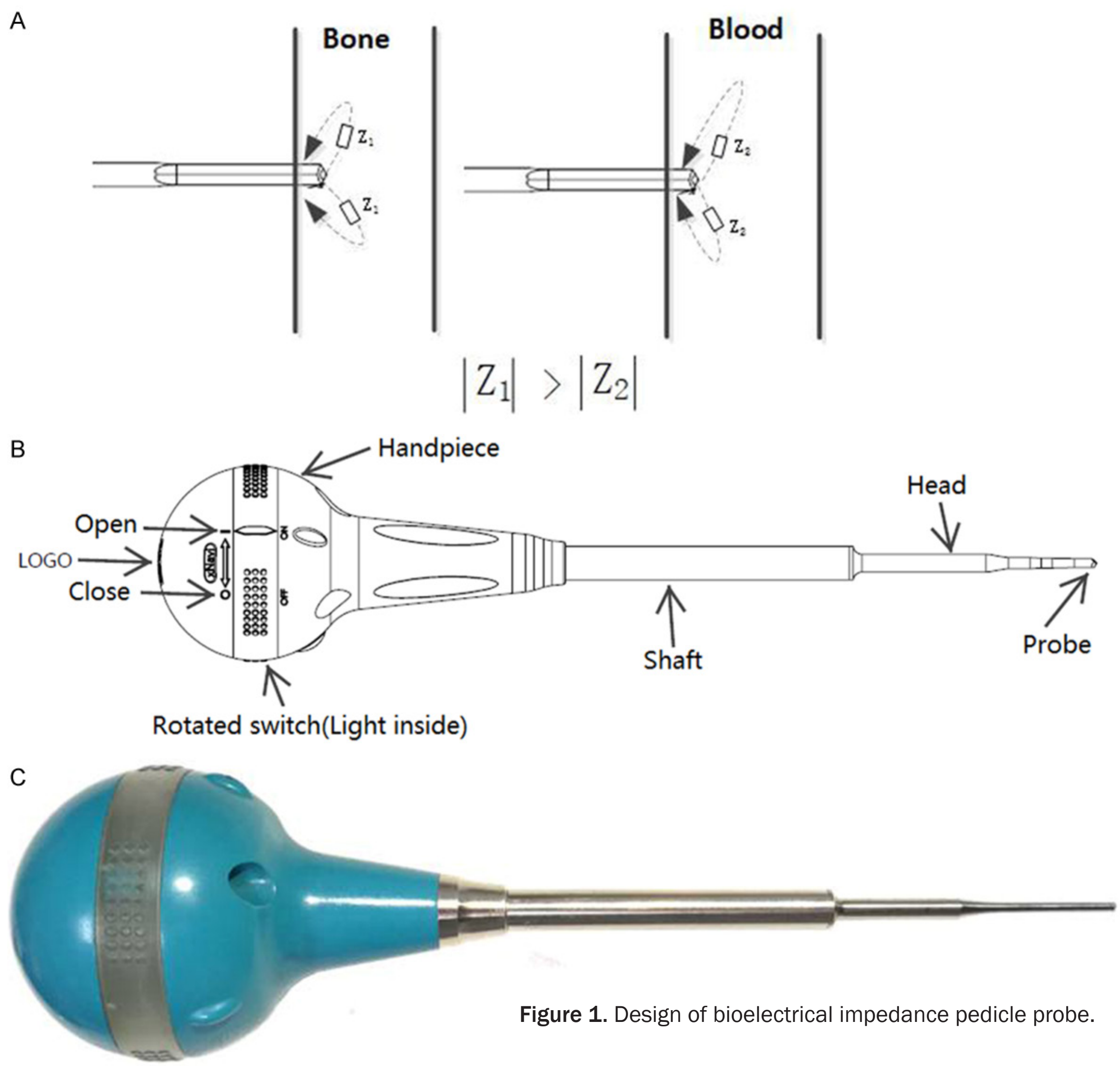

Figure 1. Design of bioelectrical impedance pedicle probe.

explored the use of a prototype bioelectrical impedance pedicle probein 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 detector and a pedicle probe, which was invented by our research group (Patent no. ZL 201520104894.9) (**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 recored *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.

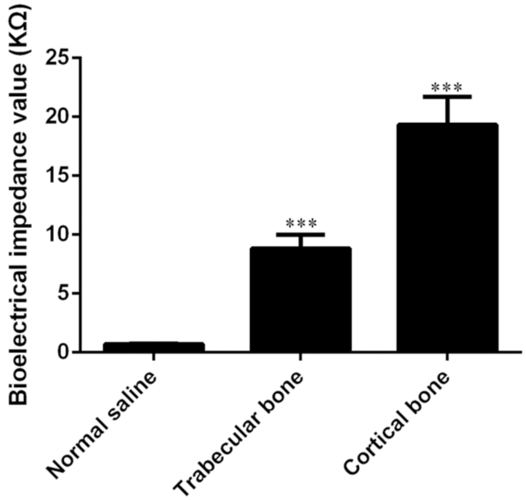

Figure 2. The bioelectrical impedance of normal saline, trabecular bone and cortical bone was shown. Difference between groups was measured by one-way ANOVA. ****P*<0.001 significantly different from normal saline.

Statistical analysis

Statistical analysis was performed using SPSS (version 18, Chicago, IL, USA). Data were shown as mean ± 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,

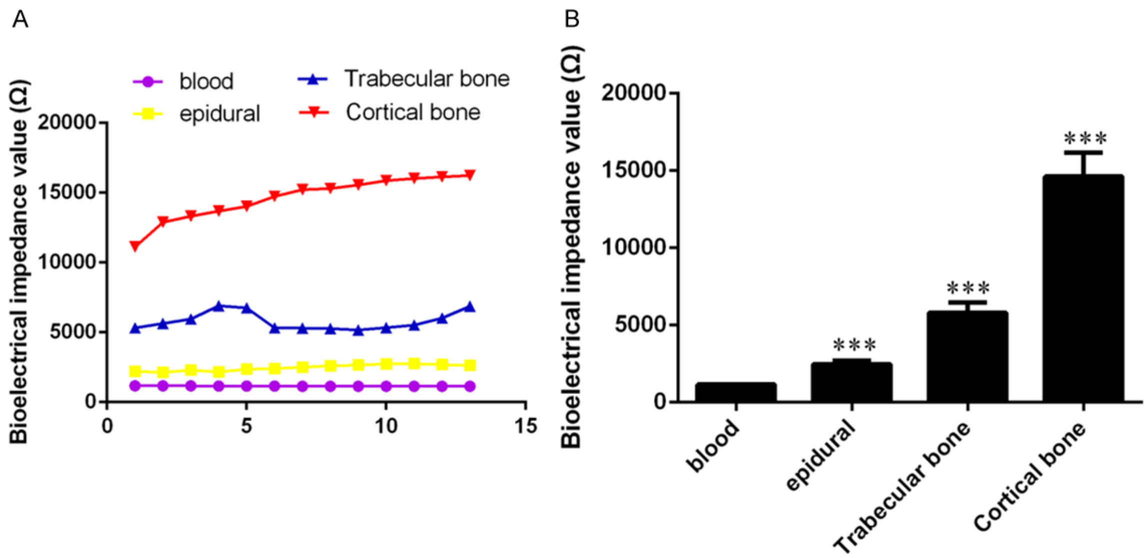

Figure 3. A. The bioelectrical impedance values of blood, dura mater, trabecular bone and cortical bone was determined *in vivo*. The x-axis indicated time. B. The bioelectrical impedance value of cortical bone was highest among the tested tissues, followed by trabecular bone, dura mater and blood. Difference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

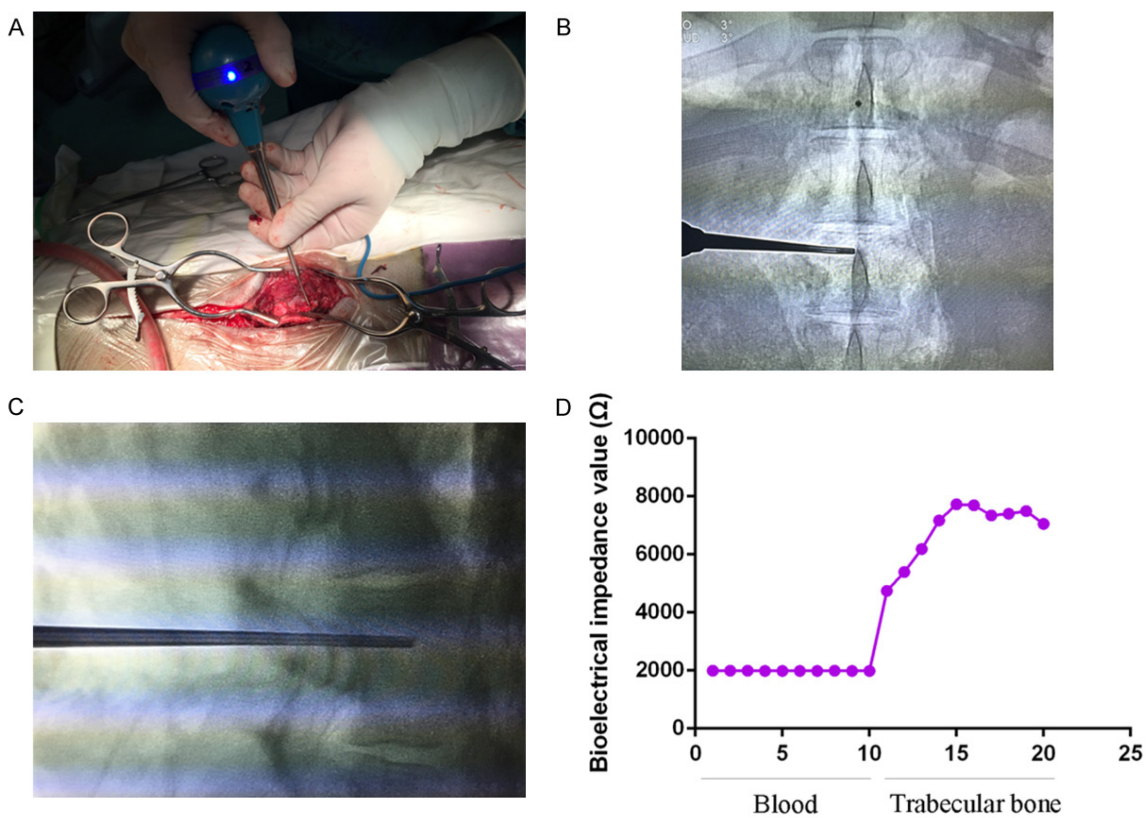

Figure 4. Testing bioelectrical impedance pedicle probe during surgery in swine. (A) This bioelectrical impedance pedicle probe, which was used in the operation. Anteroposterior (B) and lateral (C) radiographs confirmed that this pedicle screw insertion was properly done. (D) The changes in bioelectrical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

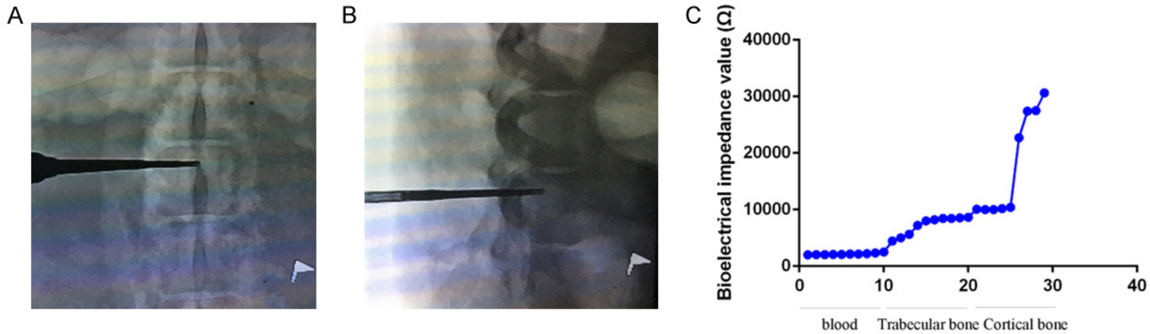

Figure 5. Utilization of pedicle probe to create a pedicle screw canal with partialdrilling of medial cortex. The creation of a pedicle screw canal with partial drilling of medial cortex was confirmed by the anteroposterior (A) and lateral (B) radiographs. (C) There were three tissues, namely blood, 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.

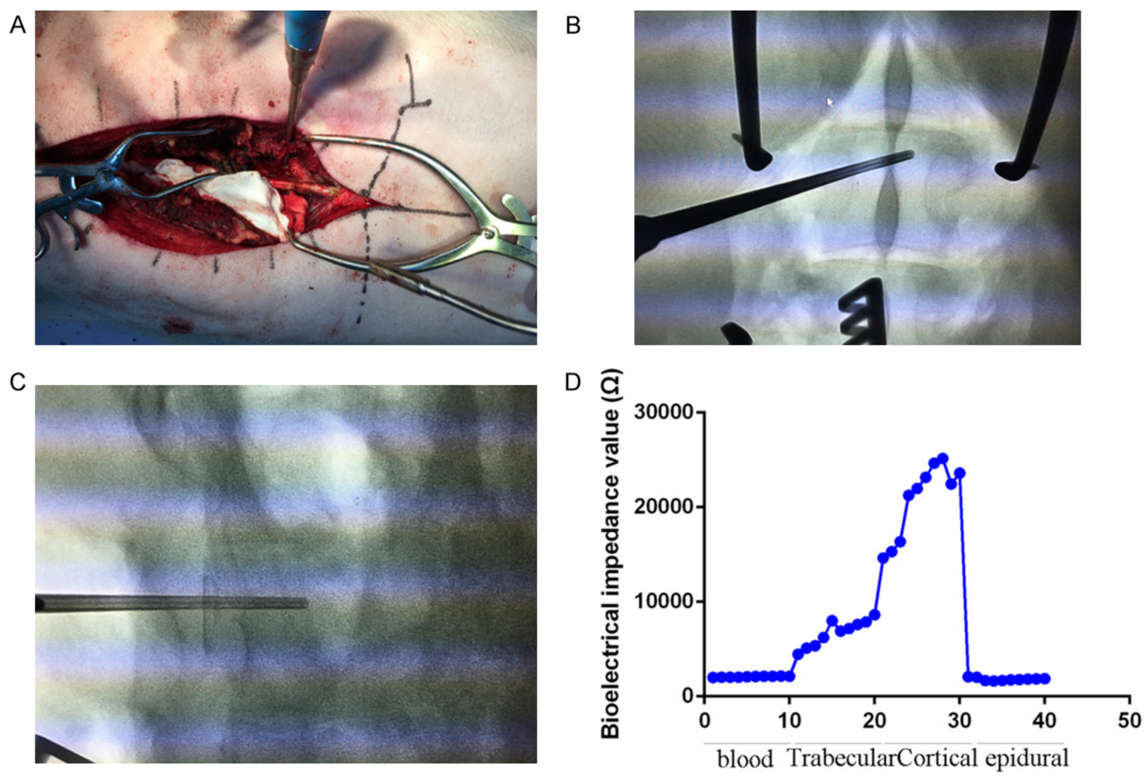

Figure 6. A pedicle screw canal that passed through the spinal canal to mimic pedicle screw misplacement. A. The insertion of pedicle probe during the operation is shown. B, C. The creation of an incorrectpedicle screw path was confirmed by anteroposterior and lateral radiographs. D. The changes in bioelectrical 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 cortexand 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 is set 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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References

[1] Liang J, Shen J, Chua S, Fan Y, Zhai J, Feng B, Cai S, Li Z and Xue X. Does intraoperative cell salvage system effectively decrease the need for allogeneic transfusions in scoliotic patients undergoing posterior spinal fusion? A prospective randomized study. Eur Spine J 2015; 24: 270-275.

[2] Li Z, Shen J, Qiu G, Yu H, Wang Y, Zhang J, Zhao H, Zhao Y, Li S, Weng X, Liang J and Zhao L. Unplanned reoperation within 30 days of fusion surgery for spinal deformity. PLoS One 2014; 9: e87172.

[3] Liu J, Shen J, Zhang J, Li S, Zhao H, Qiu G and Wang Y. The position of the aorta relative to

the spine for pedicle screw placement in the correction of idiopathic scoliosis. J Spinal Disord Tech 2012; 25: E103-107.
[4] Viezens L, Reer P, Strahl A, Weiser L, Schroeder M, Beyerlein J and Schaefer C. Safety and efficacy of single-stage versus 2-stage spinal fusion via posterior instrumentation and anterior thoracoscopy: a retrospective matched-pair cohort study with 247 consecutive patients. World Neurosurg 2018; 109: e739-e747.
[5] Lewis SJ, Mohanty C, Gazendam AM, Kato S, Keshen SG, Lewis ND, Magana SP, Perlmutter D and Cape J. Posterior column reconstruction improves fusion rates at the level of osteotomy in three-column posterior-based osteotomies. Eur Spine J 2018; 27: 636-643.
[6] Suk S, Lee C, Kim W, Chung Y and Park Y. Segmental pedicle screw fixation in the treatment of thoracic idiopathic scoliosis. Spine (Phila Pa 1976) 1995; 20: 1399-1405.
[7] Jahangiri F, Sheryar M and Al Behairy Y. Early detection of pedicle screw-related spinal cord injury by continuous intraoperative neurophysiological monitoring (IONM). Neurodiagn J 2014; 54: 323-337.
[8] Sarwahi V, Suggs W, Wollowick A, Kulkarni P, Lo Y, Amaral T and Thornhill B. Pedicle screws adjacent to the great vessels or viscera: a study of 2132 pedicle screws in pediatric spine deformity. J Spinal Disord Tech 2014; 27: 64-69.
[9] Chen L, Xu L, Qiu Y, Qiao J, Wang F, Liu Z, Shi B, Qian B and Zhu Z. The risks of aorta impingement from pedicle screw may increase due to aorta movement during posterior instrumentation in lenke 5C curve: a computed tomography study. Eur Spine J 2015; 24: 1481-1489.
[10] Baghdadi Y, Larson A, McIntosh A, Shaughnessy W, Dekutoski M and Stans A. Complications of pedicle screws in children 10 years or younger: a case control study. Spine (Phila Pa 1976) 2013; 38: E386-393.
[11] Mirza A, Alvi M, Naylor R, Kerezoudis P, Krauss W, Clarke M, Shepherd D, Nassr A, DeMartino R and Bydon M. Management of major vascular injury during pedicle screw instrumentation of thoracolumbar spine. Clin Neurol Neurosurg 2017; 163: 53-59.
[12] Sugawara R, Tsuji T, Saito T, Nohara A, Kawakami K and Kawakami N. Medially misplaced pedicle screws in patients without neurological deficits following scoliosis surgery: to observe or to remove? Eur Spine J 2015; 24: 1450-1456.
[13] Kurinami N, Sugiyama S, Morita A, Yoshida A, Hieshima K, Miyamoto F, Kajiwara K, Jinnouch K, Jinnouchi T and Jinnouchi H. Ratio of muscle mass to fat mass assessed by bioelectrical impedance analysis is significantly correlated with liver fat accumulation in patients with type 2 diabetes mellitus. Diabetes Res Clin Pract 2018; 139: 122-130.
[14] Beberashvili I, Yermolayeva T, Katkov A, Garra N, Feldman L, Gorelik O, Stav K and Efrati S. Estimating of residual kidney function by multi-frequency bioelectrical impedance analysis in hemodialysis patients without urine collection. Kidney Blood Press Res 2018; 43: 98-109.
[15] Yamada Y, Buehring B, Krueger D, Anderson R, Schoeller D and Binkley N. Electrical properties assessed by bioelectrical impedance spectroscopy as biomarkers of age-related loss of skeletal muscle quantity and quality. J Gerontol A Biol Sci Med Sci 2017; 72: 1180-1186.
[16] Samoni S, Vigo V, Reséndiz L, Villa G, De Rosa S, Nalesso F, Ferrari F, Meola M, Brendolan A, Malacarne P, Forfori F, Bonato R, Donadio C and Ronco C. Impact of hyperhydration on the mortality risk in critically ill patients admitted in intensive care units: comparison between bioelectrical impedance vector analysis and cumulative fluid balance recording. Crit Care 2016; 20: 95.
[17] Yamazoe M, Mizuno A, Niwa K and Isobe M. Edema index measured by bioelectrical impedance analysis as a predictor of fluid reduction needed to remove clinical congestion in acute heart failure. Int J Cardiol 2015; 201: 190-192.
[18] Franssen F, Rutten E, Groenen M, Vanfleteren L, Wouters E and Spruit M. New reference values for body composition by bioelectrical impedance analysis in the general population: results from the UK Biobank. J Am Med Dir Assoc 2014; 15: 448, e441-446.
[19] Gastelurrutia P, Nescolarde L, Rosell-Ferrer J, Domingo M, Ribas N and Bayes-Genis A. Bioelectrical impedance vector analysis (BIVA) in stable and non-stable heart failure patients: a pilot study. Int J Cardiol 2011; 146: 262-264.
[20] Fürstenberg A and Davenport A. Comparison of multifrequency bioelectrical impedance analysis and dual-energy X-ray absorptiometry assessments in outpatient hemodialysis patients. Am J Kidney Dis 2011; 57: 123-129.
[21] Mok E, Béghin L, Gachon P, Daubrosse C, Fontan J, Cuisset J, Gottrand F and Hankard R. Estimating body composition in children with Duchenne muscular dystrophy: comparison of bioelectrical impedance analysis and skinfold-thickness measurement. Am J Clin Nutr 2006; 83: 65-69.
[22] Bosy-Westphal A, Danielzik S, Dörhöfer R, Piccoli A and Müller M. Patterns of bioelectrical impedance vector distribution by body mass index and age: implications for body-composition analysis. Am J Clin Nutr 2005; 82: 60-68.

[23] Nielsen B, Dencker M, Ward L, Linden C, Thorsson O, Karlsson M and Heitmann B. Prediction of fat-free body mass from bioelectrical impedance among 9- to 11-year-old Swedish children. Diabetes Obes Metab 2007; 9: 521-539.
[24] Galluzzo M, D'Adamio S, Pastorino R, Andreoli A, Servoli S, Bianchi L and Talamonti M. Effect of anti IL-12/23 on body composition: results of bioelectrical impedance analysis in Caucasian psoriatic patients. Expert Opin Biol Ther 2017; 1-7.
[25] Hicks J, Singla A, Shen F and Arlet V. Complications of pedicle screw fixation in scoliosis surgery: a systematic review. Spine (Phila Pa 1976) 2010; 35: E465-470.
[26] Di Silvestre M, Bakaloudis G, Lolli F, Vommaro F, Martikos K and Parisini P. Posterior fusion only for thoracic adolescent idiopathic scoliosis of more than 80 degrees: pedicle screws versus hybrid instrumentation. Eur Spine J 2008; 17: 1336-1349.
[27] Kuklo T, Lenke L, O'Brien M, Lehman R, Polly D and Schroeder T. Accuracy and efficacy of thoracic pedicle screws in curves more than 90 degrees. Spine (Phila Pa 1976) 2005; 30: 222-226.
[28] Suk S, Kim W, Lee S, Kim J and Chung E. Thoracic pedicle screw fixation in spinal deformities: are they really safe? Spine (Phila Pa 1976) 2001; 26: 2049-2057.
[29] Agarwal A, Chauhan V, Singh D, Shailendra R, Maheshwari R and Juyal A. A comparative study of pedicle screw fixation in dorsolumbar spine by freehand versus image-assisted technique: a cadaveric study. Indian J Orthop 2016; 50: 243-249.
[30] Molliqaj G, Schatlo B, Alaid A, Solomiichuk V, Rohde V, Schaller K and Tessitore E. Accuracy of robot-guided versus freehand fluoroscopy-assisted pedicle screw insertion in thoracolumbar spinal surgery. Neurosurg Focus 2017; 42: E14.
[31] Dede O, Ward W, Bosch P, Bowles A and Roach J. Using the freehand pedicle screw placement technique in adolescent idiopathic scoliosis surgery: what is the incidence of neurological symptoms secondary to misplaced screws? Spine (Phila Pa 1976) 2014; 39: 286-290.
[32] Wang H, Liu Y, Zhao Y, Song G, Liu J, Han J and Xiang L. Feasibility and accuracy of computer-assisted individual drill guide template for minimally invasive lumbar pedicle screw placement trajectory. Injury 2018; 49: 644-648.
[33] Uehara M, Takahashi J, Ikegami S, Kuraishi S, Futatsugi T, Oba H, Koseki M and Kato H. Mid-term results of computer-assisted skip pedicle screw fixation for patients with Lenke type 1 and 2 adolescent idiopathic scoliosis: a minimum five-year follow-up study. J Orthop Sci 2018; 23: 248-252.
[34] Devito D, Kaplan L, Dietl R, Pfeiffer M, Horne D, Silberstein B, Hardenbrook M, Kiriyanthan G, Barzilay Y, Bruskin A, Sackerer D, Alexandrovsky V, Stüer C, Burger R, Maeurer J, Donald G, Gordon D, Schoenmayr R, Friedlander A, Knoller N, Schmieder K, Pechlivanis I, Kim I, Meyer B and Shoham M. Clinical acceptance and accuracy assessment of spinal implants guided with spine assist surgical robot: retrospective study. Spine (Phila Pa 1976) 2010; 35: 2109-2115.
[35] Nagai M, Komiya H, Mori Y, Ohta T, Kasahara Y and Ikeda Y. Estimating visceral fat area by multifrequency bioelectrical impedance. Diabetes Care 2010; 33: 1077-1079.
[36] Paterna S, Di Pasquale P, Parrinello G, Fornaciari E, Di Gaudio F, Fasullo S, Giammanco M, Sarullo F and Licata G. Changes in brain natriuretic peptide levels and bioelectrical impedance measurements after treatment with high-dose furosemide and hypertonic saline solution versus high-dose furosemide alone in refractory congestive heart failure: a double-blind study. J Am Coll Cardiol 2005; 45: 1997-2003.
[37] Ryo M, Maeda K, Onda T, Katashima M, Okumiya A, Nishida M, Yamaguchi T, Funahashi T, Matsuzawa Y, Nakamura T and Shimomura I. A new simple method for the measurement of visceral fat accumulation by bioelectrical impedance. Diabetes Care 2005; 28: 451-453.
[38] Faisy C, Rabbat A, Kouchakji B and Laaban J. Bioelectrical impedance analysis in estimating nutritional status and outcome of patients with chronic obstructive pulmonary disease and acute respiratory failure. Intensive Care Med 2000; 26: 518-525.
[39] Panisset M, Desneves K, Ward L, Rafferty J, Rodi H, Roff G, El-Ansary D and Galea M. Bedside quantification of fat-free mass in acute spinal cord injury using bioelectrical impedance analysis: a psychometric study. Spinal Cord 2018; 56: 355-365.
[40] Hansen E, Baigent C, Reck S and Connor M. Bioelectrical impedance as a technique for estimating postmortem interval. J Forensic Sci 2018; 63: 1186-1190.