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Porcine model in intra-operative neural monitoring in thyroid surgery

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TITLE

Intra-Operative Neural Monitoring of Thyroid Surgery in a Porcine Model

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KEYWORDS
Intraoperative neural monitoring; recurrent laryngeal nerve; external branch of the superior laryngeal nerve; vagus nerve; thyroid surgery; animal study; porcine model.

SHORT ABSTRACT
This study aims to develop a standard protocol of intra-operative neural monitoring of thyroid surgery in a porcine model. Here, we present a protocol to demonstrate general anesthesia, to compare different types of electrodes, and to investigate the electrophysiological characteristics of the normal and injured recurrent laryngeal nerves.

LONG ABSTRACT
Intraoperative injury to the recurrent laryngeal nerve (RLN) can cause vocal cord paralysis, which interferes with speech and can potentially interfere with breathing. In recent years, intraoperative neural monitoring (IONM) has been widely adapted as an adjunct technique to localize the RLN, detect RLN injury, and predict vocal cord function during the operations. Many studies have also used animal models to investigate new applications of IONM technology and to develop reliable strategies for preventing intraoperative RLN injury. The aim of this article is to introduce a standard protocol for using a porcine model in IONM research. The article demonstrates the procedures for inducing general anesthesia, performing tracheal intubation, and experimental design to investigate the electrophysiological characteristics of RLN injuries. Applications of this protocol can improve overall efficacy in implementing the 3R principle (replacement, reduction and refinement) in porcine IONM studies.

INTRODUCTION:
Although thyroidectomy is now a commonly performed procedure worldwide, postoperative voice dysfunction is still common. Intraoperative injury to the recurrent laryngeal nerve (RLN) can cause vocal cord paralysis, which interferes with speech and can potentially interfere with breathing. Additionally, injury to the external branch of the superior laryngeal nerve can cause a major voice change by affecting pitch and vocal projection.

Intraoperative neural monitoring (IONM) during thyroid operations has obtained wide popularity as an adjunct technique for mapping and confirming the RLN, the vagus nerve (VN), and the external branch of the superior laryngeal nerve (EBSLN). Because IONM is useful for confirming and elucidating mechanisms of RLN injury and for detecting anatomic variations in the RLN, it can be used to predict vocal cord function after thyroidectomy. Therefore, IONM adds a new functional dynamic in thyroid surgery and empowers surgeons with information that cannot be obtained by direct visualization alone[1-10].

Recently, many prospective studies have used porcine models to optimize the use of IONM technology and to establish reliable strategies for preventing intraoperative RLN injury[11-20].Porcine models have also been used to provide practitioners with essential education and training in clinical applications of IONM.

Therefore, the combination of animal models and IONM technology is a valuable tool for studying the pathophysiology of RLN injury[21]. The aim of this article was to demonstrate the use of a porcine model in IONM research. Specifically, the article demonstrates how to induce general anesthesia, perform tracheal intubation, and set up experiments for investigating the electrophysiological characteristics of various RLN injury types.

PROTOCOL

The animal experiments were approved by the Institutional Animal Care and Use Committee (IACUC) of Kaohsiung Medical University, Taiwan (protocol no: IACUC-102046, 104063, 105158).

1. Animal Preparation and Anesthesia

1.1. Porcine animal model

Note: This study applied the protocol described in the literature to establish a prospective porcine model of IONM[11-19,22].

1.1.1. Use KHAPS Black or Duroc-Landrace pigs (3-4 months old; weighing 18-30 kg).

1.1.2. Ensure that the experimental protocol is consistent with national/international regulations and guidelines for animal experiments, including the 3R principles (replacement, reduction, and refinement). Obtain ethical approval of the experimental protocol from the committee for care and use of experimental animals at the relevant institution.

1.2. Anesthesia induction

1.2.1. Pre-anesthesia preparations

1.2.1.1. Withhold food 8 hours before anesthesia and withhold water 2 hours before anesthesia.

1.2.1.2. Pre-medicate with intramuscular azaperone (4 mg/kg) at 2 hours before anesthesia. Use a 500 mL saline bottle to fabricate a face mask for each piglet. Trim as needed to ensure a secure fit to the snout.

1.2.1.3. Use the weighing function on the operating table to measure the net weight of each piglet **(Figure 1A)**.

1.2.1.4. Maintain body temperature with a circulating water mattress set to 40 °C.

1.2.2. Induce general anesthesia (GA) with 2-4% sevoflurane at a fresh gas flow of 3 L/min *via* the face mask with the piglet in a prone position. An adequate depth of anesthesia is usually achieved in 3-5 minutes. Confirm the depth of anesthesia by no severe movement to pain due to peripheral venous catheterization.

1.2.3. Identify a superficial vein on the outer side of one ear and sterilize the selected region (about 6 x 6 cm^2) with 75% alcohol. For maximum safety, use a 24-gauge peripheral intravenous catheter.

1.2.4. Administer intravenous anesthetic such as propofol (1-2 mg/kg) or thiamylal (5-10 mg/kg) to alleviate noxious stimulation by direct laryngoscopy.

Note: Use of neuromuscular blocking agent (NMBA) is not suggested. In subsequent experiments, NMBA may complicate intubation by depressing spontaneous breathing and may diminish electromyography (EMG) signals. Additionally, sevoflurane inhalation combined with a bolus of propofol or short-acting barbiturates is reportedly sufficient for facilitating tracheal intubation.

1.3. Tracheal intubation **(Figure 1B)**

1.3.1. Prepare the equipment and materials required for EMG tube intubation: a size #6 EMG endotracheal tube, a face mask for assisted ventilation, two slings to hold the mouth open, one gauze strip to pull the tongue, a blunt tip suction catheter, a veterinary laryngoscope with 20cm straight blades, an elastic bougie, a 20-mL syringe, a stethoscope, and adhesive tape.

1.3.2. Position the piglet in a prone position on the operating table. Align the head and body to ensure clear visualization of the upper airway.

1.3.3. Direct the assistant to apply traction of the upper and lower jaw to maintain an adequate mouth opening and to avoid rotation or overextension of the head. Cover the tongue with gauze and pull the tongue out to optimize the visual field.

1.3.4. Hold the laryngoscope upside down and place it directly in the oral cavity to depress the tongue.

1.3.5. Directly visualize the epiglottis and use the laryngoscope to press the epiglottis downward toward the tongue base.

1.3.6. When the vocal cords are clearly identified, gently advance the elastic bougie into the trachea. Slight rotation of the elastic bougie may be required to overcome resistance. Next, advance the EMG tube at the mouth angle to a depth of 24 cm.

1.3.7. Inflate the EMG tube cuff to a volume no larger than 3 mL. If ventilation by manual bagging reveals no obvious air leakage, *in situ* deflation of the EMG tube is feasible.

1.3.8. When the EMG tube is placed at the proper depth, confirm the free passage of fresh gas by manual bagging. Further confirm the proper tracheal intubation by end-tidal carbon dioxide ($etCO_2$) monitoring (capnography) and chest auscultation for early identification of inadvertent esophageal or endobronchial intubation.

Note: Capnography showed both the $etCO_2$ waveform and the digital value in mmHg. When esophageal intubation occurred, $etCO_2$ was absent or near zero after 6 breaths. When the EMG tube was in the correct place, the typical $etCO_2$ waveform and adequate value (usually >30 mmHg) was noted. Furthermore, the breathing sound of a bilateral lung filled is clear and symmetric as determined by chest auscultation.

1.3.9. Use medical tape to fix the EMG tube at the mouth angle. Since the tube usually requires adjustment during IONM experiments, do not fasten the tube to the snout.

1.3.10. Connect the EMG tube to the ventilator. Continuous capnography is mandatory for monitoring the $etCO_2$ value and curve throughout the experiment.

1.4. Anesthesia maintenance **(Figure 1C)**

1.4.1. After the EMG tube is fixed, position the piglet on its back with the neck extended (**Figure 1C**). Maintain general anesthesia with 1-3% sevoflurane in oxygen at 2 L/min.

1.4.2. Ventilate the lungs in volume-control mode at a tidal volume of 8-12 mL/kg, and set the respiratory rate to 12-14 breaths/min.

1.4.3. Begin physiologic monitoring, including capnography, electrocardiography (ECG)and monitoring of oxygenation (SaO_2).

2. Equipment Setting and Animal Operation (Figure 1D)

2.1. Equipment Setup

2.1.1. Connect the channel leads from the EMG tube to the monitoring system.

2.1.2. Set the monitoring system to run 50 ms time window. Set pulsed stimuli to 100 μs and 4 Hz. Set the event capture threshold to 100 μV.

2.2. Surgical procedure

2.2.1. Wear sterile surgical gloves and use povidone iodine with cotton swabs to disinfect the neck surgical site.

2.2.2. Use a transverse collar incision about 10-15 cm in length with a scalpel to expose the neck and the larynx.

2.2.3. Raise the subplatysmal flap 1 cm cranially from the clavicle to the hyoid bone.

2.2.4. Remove the strap muscles and visualize the tracheal rings and nerves. Use monopolar and bipolar electrocautery to assist the surgical dissection and hemostasis.

2.2.5. Localize, identify, and carefully expose the EBSLN, RLN, and VN with a handheld stimulation probe.

2.2.6. Position an automated periodic stimulation (APS) electrode on one side of VN for stimulating during continuous IONM (CIONM). Connect the APS electrode with the monitoring system. Set pulsed stimuli to 1 Hz, 100 μs, and 1 mA.

2.3. At end of experiments, euthanize all piglets by the veterinarian.

3. Electrical Stimulation

Note: To apply the 3R principle in porcine IONM studies, always perform repeatable electrophysiology studies that do not cause nerve injury before performing experiments that may cause nerve injury. This can be used to study the intensity, safety, and cardiopulmonary effects[11,17]. The IONM equipment can be classified as stimulation equipment or recording equipment (**Figure 2A**).

3.1. Evaluate the baseline EMG responses of the target nerves, including the EBSLN, RLN, and VN **(Figures 2B, 2C)**.

3.1.1. Start with an initial stimulation current of 0.1-mA current and increase stimulation in 0.1-mA increments until an EMG response is detected and recorded.

3.1.2. Further increase the current until the maximal EMG response is obtained.

3.1.3. Record the baseline amplitude, latency, and waveform of the EMG response.

3.1.4. Define the minimal stimulus level as the lowest current (mA) that clearly evoked EMG activity of >100 μV. Define the maximal stimulus level as the lowest current that evoked the maximal EMG response.

3.2. Evaluate the Safety of electrical stimulation[11,19]

3.2.1. Apply a continuous 1-minute stimulus at the fifth tracheal ring level of the VN or RLN.

3.2.2. Progressively increase the stimulus current from 1 mA to 30 mA.

3.2.3. During VN stimulation, evaluate hemodynamic stability by monitoring of heart rate, ECG, and invasive arterial blood pressure.

3.2.4. Finally, evaluate nerve function integrity by comparing EMG responses proximal to the nerve stimulation site before and after each level of stimulation is applied.

3.3. Effect of anesthetics (muscle relaxants and their reversals)[12,20]

Note: Improper use of NMBAs is a potential cause of unsuccessful IONM. The proposed animal model was used to compare recovery profiles among different depolarizing NMBAs (*e.g.,* succinylcholine) and nondepolarizing NMBAs (*e.g.*, rocuronium) at varying doses and to identify the optimal NMBA for use in IONM. The animal model can also be used to evaluate the effectiveness of NMBA reversal drugs (*e.g.*, sugammadex) for rapidly restoring neuromuscular function suppressed by rocuronium.

3.3.1. ~~Perform continuous IONM (C-IONM) to investigate real-time EMG changes. in the VN under automated periodic stimulation (APS).~~
Firstly, apply C-IONM and use the automatically calibrated baseline latencies and amplitudes of EMG as control data.

3.3.2. Administer a bolus injection of ~~tested NMBA (~~rocuronium 0.3mg/kg in a volume of 10mg per ml and observe the real-time EMG changes

3.3.3. Three minutes after injection ~~of the tested NMBA~~, perform one injection of sugammadex 2mg/kg in a volume of 100mg/ml ~~the tested reversal drug~~ as a rapid bolus. ~~–~~Record the recovery profile of laryngeal EMG for 20 minutes.

3.4. Stimulation electrodes (Stimulation probes/dissectors) **(Figure 3)[17]**

Note: There are different types of stimulation electrodes that can be used for nerve stimulation during IONM, *e.g.*, monopolar probes (**Figure 3A**), bipolar probes (**Figure 3B**), and stimulation dissectors (**Figure 3C**).

3.4.1. To mimic direct stimulation of nerves during surgery, apply 1mA stimulation to the EBSLN, RLN, and VN without overlying fascia.

Commented [A1]: How is C-IONM done? Please specify exactly. Much of the later protocol references C-IONM.

Commented [A2R1]: Procedures and settings of CIONM has been added to 2.2.6

Commented [A3]: How much is injected? What amount and what volume?

Commented [A4R3]: rocuronium 0.3mg/kg in a volume of 10mg per ml

Commented [A5]: What stimulation is applied?

3.4.2. To mimic indirect mapping and localizing of the nerve position before visual identification during surgery, apply 1mA stimulation at a 1- ~~or~~ and 2-mm distance away from the ~~EBSLN, RLN, and VN or~~nerves at overlying fascia.

3.4.3. Record and compare the EMG responses between different types of stimulation electrodes.

3.5. Recording electrodes (EMG tubes/ needle electrodes/ pre-gelled skin electrodes)**(Figure 4)**[23,24]

3.5.1. Use the animal model to evaluate how rotation or upward/downward displacement of the EMG tube electrode (**Figure 4A**) affects the stability of the EMG signal. Additionally, use the animal model to compare the EMG responses between different electrode types (*e.g.*, needle electrodes and adhesive pre-gelled electrodes, **Figure 4B**) and different recording approaches (*e.g.*, transcutaneous/percutaneous and transcartilage approaches, **Figures 4C and 4D**) in terms of feasibility, stability, and accuracy during IONM.

3.5.2. For a feasibility study, apply a 1-mA stimulus current to bilateral EBSLNs, VNs and RLNs. Record and compare EMG responses evoked by each electrode tested (*i.e.,* EMG tube, transcutaneous, percutaneous, and transcartilage electrodes).

3.5.3. For a stability study, evaluate and compare EMG signal stability in C-IONM under experimentally induced cricoid/tracheal cartilage displacement.

3.5.4. For an accuracy study, evaluate and compare the accuracy of the tested electrodes in C-IONM for identifying EMG signal degradation under RLN injury.

4. **RLN injury study (Figure 5)**

4.1. In accordance with the 3R principle, perform RLN injury experiments in the porcine model after all repeatable electrophysiology studies are completed. Perform tests of nerve segments from proximal nerve segments to distal nerve segments (*i.e.,* proceed from the caudal part of the RLN to the cranial part of the RLN).

4.2. Use C-IONM to confirm and compare patterns of real-time changes in evoked laryngeal EMG signals during and after acute RLN injuries with different injury mechanisms (*e.g.*, traction, clamping, transection, or thermal injuries) **(Figures 5A and 5B)**. Use C-IONM for continuous real-time display and recordation of EMG changes and sequential recoveries throughout the experiment (**Figure 5C**).

4.3. Collect injured RLN segments for histopathological analysis of morphological alterations caused by the nerve injury experiments.

4.4. Traction compression/stretch injury

Commented [A6]: What stimulation is applied?

Commented [A7R6]: 1mA

Commented [A8R6]: 1mA

Note: Traction compression or stretch injuries are the most common intraoperative RLN injuries. Experimentally induce traction stress and observe the resulting electrophysiological EMG changes and histopathological changes.

4.4.1. Traction compression injury[13]

4.4.1.1. Wrap a thin plastic loop (*e.g.*, a vascular loop 1.3-mm wide) around the RLN and use a force gauge to apply retraction with 50 g of tension ~~under varying tension~~ (**Figure 5A**). This scheme mimics an RLN trapped against a dense, fibrous band or a crossing artery at the region of Berry's ligament during medial traction of the thyroid lobe.

Commented [A9]: Please quantitate the tension. How much tension?

Commented [A10R9]: 50 g

4.4.2. Traction stretch injury[16]

4.4.2.1. Wrap the RLN with a wider elastic material (*e.g.*, a 10-mm wide silicone Penrose drain), and use a force gauge to retract the RLN with 50 g of tension ~~under varying tension~~) This scheme mimics an RLN adhered to or encased in the goiter capsule and stretched forward during medial traction.

Commented [A11]: Please quantitate the tension. How much tension?

Commented [A12R11]: 50 g

4.5. Clamping injury ~~and transection injuries~~

Commented [A13]: Is this done after steps 4.4.1.2 and 4.4.2.1?

Commented [A14R13]: Re: Yes, "After the traction compression RLN injury experiment,…"

Note: Intraoperative mechanical trauma to the RLN usually results from poor exposure or visual misidentification of the RLN. [13,16]

4.5.1. After the traction compression RLN injury experiment, pinch the distal segment of the RLN with hemostatic forceps for one second. This scheme mimics the nerve being inadvertently clamped owing to visual misidentification as a vessel during the operation. ~~Use hemostatic forceps to clamp the RLN under varying force/duration, or use a knife to perform a partial or total transection.~~ Record the accompanying EMG signal change for comparison with further histopathological findings of the nerve specimen.

Commented [A15]: What parameters are used?

Commented [A16R15]: We pinch the nerve with hemostatic forceps for 1s. There is no need for quantifying the pressure for this experiment. Surgery.155 (2), 329-339 (2014); World J Surg.40 (6), 1373-1381 (2016).

4.6. Thermal injury

Note: Most intraoperative RLN thermal injuries result from thermal spread when electrocautery devices and various energy-based devices (EBDs) are used to induce hemostasis near the RLN. Like traction injury, thermal injury is rarely visible to the naked eye. Therefore, perform animal IONM experiments to determine the best model for evaluating the pathophysiology of RLN thermal injury and to test the thermal tolerance[14] and the safety of EBDs[15,18].

~~Thermal tolerance study~~

~~Critical Temperature Study~~

~~Use normal saline (NS) heated to varying temperatures (from 40 to 80 °C) to irrigate the exposed RLN in the muscle pocket anterior to the sternocleidomastoid muscle.~~

~~In C-IONM, continuously irrigate the RLN exposed in the muscle pocket for 60 s with NS heated to 40 °C.~~

~~If no EMG event occurs, increase the temperature at a 10 °C increase , and repeat the tests in the same RLN until an EMG change is observed. Define the critical temperature (C temperature) as the threshold temperature at which the EMG event occurs.~~

~~Thermal Dose Study~~

~~Perform a thermal dose study for further comparison of temperature-induced EMG waveform alterations and recovery patterns after exposure to NS heated to varying fixed temperatures (*e.g.*, C temperature, C temperature plus 10°, *etc.*) for varying durations.~~

~~Continuously monitor all real-time EMG signals for at least 20 minutes after irrigation, and determine whether the EMG waveforms recover.~~

~~EBD study[15,18]~~

4.6.1. Use C-IONM to register the EMG changes continuously throughout the experiment.

4.6.2. Activation Study - To investigate how Energy-based devices (EBD) can be safely applied for hemostasis and dissection near the RLN during surgery (**Figure 5B**).

4.6.2.1. Activate the EBD (electrothermal bipolar vessel sealing system, set power at level 2, and the energy discontinues automatically by 2 to 4 seconds) at 5-mm distance away from the RLN.

~~Perform this test from the proximal to distal segments of the RLN. Measure the distance from the tip of the EBD to the RLN. Generally, test the widest distance (*e.g.*, 5-mm distance between the EBD and the RLN) at the lowest level (*e.g.*, fifth tracheal ring).~~

4.6.2.2. If EMG signals remain stable after several tests, perform a further test at the narrower distance (*e.g.*, 2-mm, and followed by 1mm distance)

4.6.2.3. If any substantial EMG change occurs after any test the experiment is complete and followed by continuous real-time EMG recording for at least 20 minutes.

4.6.3. Cooling Study- To evaluate the cooling time to determine postactivation optimal EBD cooling parameters.

~~Perform this study to evaluate cooling time and to evaluate the effectiveness of the muscle-touch cooling maneuver used to confirm safe EBD–RLN contact after prior activation. First, activate the muscle surrounding the EBD for several seconds.~~

4.6.3.1. Contact the activated EBD on the RLN directly after a 5 second cooling time.

Commented [A17]: What temperatures? Is this filmed? It would be discontinuous.

Commented [A18R17]: We agree with your concern; the temperature study will be very difficult to film. We decide to delete this section in protocol and focus only on the EBD study.

Commented [A19]: By how much?

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Commented [A21]: How is the test done? What is actually done?

Commented [A22R21]: We will use the Ligasure small jaw (electrothermal bipolar vessel sealing system), to perform/ film the experiment

4.6.3.2. If the EMG signals remain stable after three tests, test the shorter cooling time (*e.g.*, 2 seconds, and followed by 1 second)

4.6.2.4. If the EMG remains stable after repeated tests, confirm the safety of the EBD by touching the RLN immediately after activation.

REPRESENTATIVE RESULTS:

Electrophysiology study

Baseline EMG data, minimal/ maximal stimulus level, and the stimulus-response curves

Using a standard monopolar stimulating probe, the obtained minimal stimulation level for VN and RLN stimulation is ranging from 0.1 to 0.3 mA, respectively. In general, the stimulus current correlated positively with the resulting EMG amplituderesponse.[11,17] The EMG amplitude plateaued at the maximal stimulation levels of 0.7 mA for VN stimulation, and 0.5 mA for RLN stimulation.[11]

Electrical stimulation (intensity, safety, and cardiopulmonary effect)

In the safety study, there is no unwanted effects on EMG signal or hemodynamic stability observed after continuous pulsatile VN and RLN stimulations in the setting of 1 mA to 30 mA. In addition, baseline EMG amplitudes and latencies of the VN or RLN were relatively unchanged after the nerves was stimulated by a high-current. Therefore, it was suggested that an intermittent high stimulus current during IONM was not harmful to the VN or RLN.[19]

Effects of anesthetics (muscle relaxants and their reversals)

Experimental comparisons of NMBAs of this animal model showed that different types and doses of muscle relaxants have different natural recovery profile. For example, recovery times for succinylcholine (1 mg/kg) and low-dose rocuronium (0.3 mg/kg) were significantly shorter than that for standard dose rocuronium (0.6 mg/kg). The experiments for NMBA reversals confirm that sugammadex (reversal of rocuronium) effectively and rapidly restores neuromuscular function suppressed by rocuronium.[20]

Stimulating electrodes (stimulation probes and dissecting stimulators)

Typically, IONM is performed with a commercially available ETT-based surface recording electrode system (*i.e.,* a so-called EMG tube). However, a limitation of the clinical use of EMG tubes is the need to maintain constant contact between the electrodes and vocal cords during surgery to obtain a robust EMG signal. False IONM results can result from an EMG tube that is mispositioned during intubation (*e.g.*, due to incorrect insertion depth, incorrect tube size, or rotation of the electrode) or from an EMG tube that is displaced during surgical manipulation or neck retraction (*e.g.*, causing rotation or upward /downward displacement of the electrode). Experimental comparisons of stimulating electrodes showed that the stimulation probes/dissectors evoked typical EMG waveforms from the EBSLN/RLN/VN with 1 mA current. The stimulating current correlated positively with the resultant EMG amplitude. In monopolar probes and stimulating dissectors, maximum EMG was elicited by <1mA.In bipolar probes, maximum EMG required a higher current. In all groups, evoked EMG amplitudes decreased as the distance from the probe/dissector to the nerve increased. Evoked EMG amplitudes also

decreased in stimulated nerves that had overlying fascia. Therefore, the animal model confirmed that both stimulation dissectors and conventional probes are effective to evoke EBSLN, RLN, and VN waveforms to monitor real-time nerve function during surgery[17]. Various stimulation probes/ dissectors are now available in IONM system for specific stimulation requirements, surgical monitoring application and the preference of the users.

Recording electrodes (EMG tubes, needle electrodes, and pre-gelled skin electrodes)
The feasibility study confirmed that the EMG tube electrodes on the vocalis, the transcutaneous/percutaneous needle electrodes, and the transcutaneous/transcartilage pre-gelled electrodes were effective for recording typical evoked laryngeal EMG waveforms from the VN and RLN under 1 mA stimulation.[23,24] **Figure 6** shows that transcutaneous/transcartilage pre-gelled electrodes generally recorded lower EMG amplitudes compared to EMG tube and needle electrodes.

In the stability study, real-time EMG tracings were compared before and after tracheal displacement was experimentally induced. **Figure 7** shows that the change in contact between EMG tube electrodes and vocal folds after tracheal displacement significantly changed the recorded EMG signals. However, tracheal displacement had no apparent effect on electrode contact quality or on EMG signal quality from the transcutaneous or transcartilage electrodes. The accuracy study evaluated the accuracy of real-time signals in reflecting adverse EMG degradation during RLN stress experimentally induced by continuous VN stimulation with the APS electrode. When RLN traction stress was experimentally induced, the EMG tube electrodes on the vocalis muscle and the transcartilage/percutaneous/transcutaneous electrodes recorded similar patterns of progressive degradation in EMG amplitude **(Figure 8)**.

B. RLN injury study
Traction injury
Typical real-time EMG changes during RLN traction revealed a progressive amplitude decrease combined with a latency increase (the so-called “combined event”). In addition, the EMG signals gradually recovered after release of traction **(Figure 9A)**. The histopathology study showed that morphological changes occurred mostly in outer nerve structures such as the epi- and peri-neurium. Structures in the endoneurium remained relatively intact.[13,16]

Clamping injury ~~and transection injuries~~
All RLNs showed an immediate LOS (within less than 1 s) after acute mechanical injury was experimentally induced. In addition, no gradually EMG recovery can be observed in a short period of time after the injury **(Figure 9B)**. The histopathology study showed that distortion of the epineurium and perineurium was greater in the clamping injury group compared to the traction injury group. [13,16]

Thermal injury
During the thermal injury study, the real-time EMG reveals a combined event, which then rapidly degrades to LOS **(Figure 9C)**. The reaction time before LOS and the severity of electrophysiologic injury may be related to the dose of thermal stress.[14] Studies of EBDs reveal

that the safe activation distance to the RLN and the cooling time vary by EBD type. For example, the safe activation distances and cooling times are 5 mm and 1 second for monopolar electrocautery (15 watts), 3 mm and 1 second for bipolar electrocautery (30 watts), 2 mm and 3 to 10 seconds for Harmonic scalpel, and 2 mm and 2 to 5 seconds for Ligasure system, respectively. Notably, the Harmonic scalpel should be cooled for more than 10 seconds or cooled by a quick (2 seconds) muscle touch maneuver before it touches the RLN. The Ligasure system should be cooled for more than 2 seconds or cooled by a quick muscle touch maneuver before it touches the RLN.[15,18] The histopathological examination of the thermal injured nerves showed relatively severe damage to the inner endoneurium with less distortion of the outer nerve structure.[16]

FIGURE AND TABLE LEGENDS

Figure 1. Preparation and anesthesia of KHAPS Black/ Duroc-Landrace Pigs for IONM research. (A) Net weight of each piglet was measured before anesthesia. (B)An assistant maintained an adequate mouth opening while traction was applied to the upper and lower jaw. A laryngoscope was then used to press the epiglottis downward toward the base of the tongue. When the vocal cords were clearly identified, the elastic bougie was gently advanced into the trachea. The EMG tube was then inserted to a depth of 24 cm at the appropriate mouth angle. (C) The piglet was placed on its back with the neck extended. The channel leads from the recording electrodes were connected to the monitoring system. Physiologic monitoring was performed during the study. (D) The neck and the larynx were exposed for experiments.

Figure 2The multifaceted electronic equipment and principle of the IONM system. (A)The basic equipment included the neural stimulating electrodes (stimulator) and the recording electrodes (connected to the ETT). (B) The stimulating electrodes can be used to determine the location and functional status of the EBSLN, RLN, and VN during IONM. (C) The evoked EMG response is displayed on an LCD screen.

Figure 3. The various stimulation electrodes available for use in IONM. (A) monopolar probes (B) bipolar probes, and (C) stimulation probes/dissectors. The selection of stimulation probes/ dissectors used for IONM depends on the specific stimulation requirements, the specific application desired and the preference of the surgeon.

Figure 4. Various recording electrode types are available for use in IONM. (A) The EMG ETT electrodes include (1a) Trivantage (1b) Contact Reinforced (1c)--Standard Reinforced, and (1d)-FLEX EMG Tubes); (B) (2)-adhesive pre-gelled electrodes and (3)-needle electrodes. (C and D) The EMG tube is designed to touch the vocal fold through intubation (I), and the adhesive pre-gelled or needle electrodes can be used in transcutaneous (II), percutaneous (III), or transcartilage (IV) approach for EMG recording during IONM.

Figure 5. Continuous IONM was performed *via* APS of the VN (*) to investigate real-time EMG changes in the RLN during (A) traction and (B) thermal injury. (C). Throughout the experiment,

the C-IONM system displayed and continuously recorded the induced EMG changes and sequential recoveries in real time.

Figure 6. Comparison of evoked EMG responses between four different types of recording electrodes. The feasibility studies indicated that all electrode types (*i.e.,* EMG tube, transcutaneous, percutaneous, and transcartilage electrodes) accurately recorded typical evoked laryngeal EMG waveforms from the RLN under 1 mA stimulation.

Figure 7. Comparison of real-time EMG tracings before and after experimental tracheal displacement. For stability study, tracheal displacement was experimentally induced.Changes in contact between the EMG tube electrodes and vocal folds caused significant variation in recorded EMG signals.(A) Electrodes in the normal position recorded strong EMG signals. (B) Electrodes with slight upward displacement (1cm) recorded relatively weaker EMG signals. (C) Electrodes with moderate to severe upward displacement (2cm) showed an EMG LOS.

Figure 8. Comparison of real-time EMG tracings during experimental RLN experimental RLN traction injuries between four different types of recording electrodes. The accuracy studies showed that, when RLN traction stress was experimentally induced, all electrode types (*i.e.,* EMG tube, transcutaneous, percutaneous, and transcartilage electrodes) recorded similar patterns of progressively degrading EMG amplitude.

Figure 9. Comparison of real-time EMG changes and sequential recoveries after different RLN injury types. (A) In traction injury, the EMG signals gradually degraded under nerve stress and gradually recovered after release of traction. (B) In clamping injury, the EMG signals showed an immediate LOS and no recovery. (C) In thermal injury, the EMG signals revealed a combined event and then rapidly gradually degraded to LOS with no recovery.

DISCUSSION

Injury to the RLN and EBSLN remains a significant source of morbidity caused by thyroid surgery. Until recently, nerve injury could only be identified by direct visualization of trauma. The use of IONM now enables further functional identification of the RLN by applying stimulation and recording the contraction of the target muscles. Currently, however, both conventional intermittent and continuous IONM systems have some technical limitations in false-positive and false-negative interpretations. Hence, suitable animal models are necessary to these clinical issues.

Recently, plenty of animal experimental studies have tried to overcome pitfalls of IONM and to investigate new applications. Most of these studies have used medium-sized animals such as canine/dog [25-27]and porcine/swine/mini-pig [11-19,22,28-31]. Canine models of the RLN and laryngeal function are well-established and highly mimic human anatomy, size and physiology. The porcine model is the oldest animal applied in RLN research[32,33]. The first experiments in live pigs performed by Galen in the second century A.D. demonstrated functional alterations in a transected RLN. Currently, the porcine model is most commonly used for IONM research because its anatomy and physiology are very similar to those in humans. Experimental pigs

have a medium size that enables easy handling and are widely available at a relatively low cost[21].

This instructional video demonstrates our standard protocols for using the porcine model in IONM research, including protocols for general anesthesia and tracheal intubation. The 3R principle is implemented in the design of experiments for investigating electrophysiological characteristics of RLN injuries. Key issues in the use of the proposed porcine model include(1) EMG parameter characteristics and safety considerations when applying electrical stimulation,[11,17,19](2) the use of muscle relaxants and reversals,[12,20,34](3) stimulating and recording electrodes,[17,23,24]and, most importantly (4) models of RLN injuries[13-16,18]that cannot be accurately quantified in humans. The protocols were setup to induce different severity and types of RLN injuries. Recorded real-time EMG data were correlated with postoperative vocal cord function and histopathology examinations. Although some data from experimental studies are inapplicable to clinical practice, our porcine model provides a valuable research platform not merely in understanding technology of IONM, but also in guiding future experiments to improve surgical strategies for lesser RLN injuries during thyroid surgery.

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DISCLOSURES

The authors have nothing to disclose.

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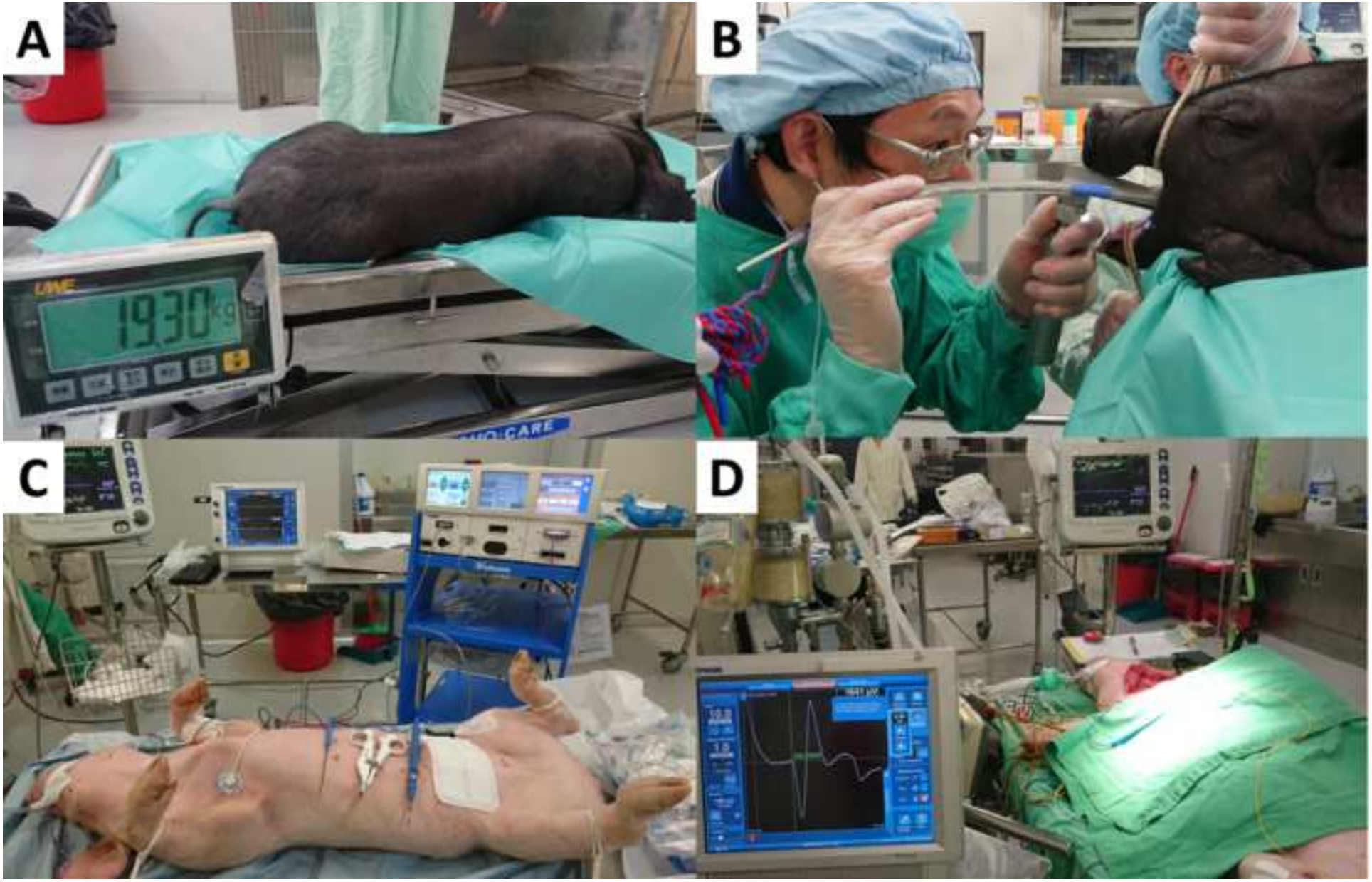

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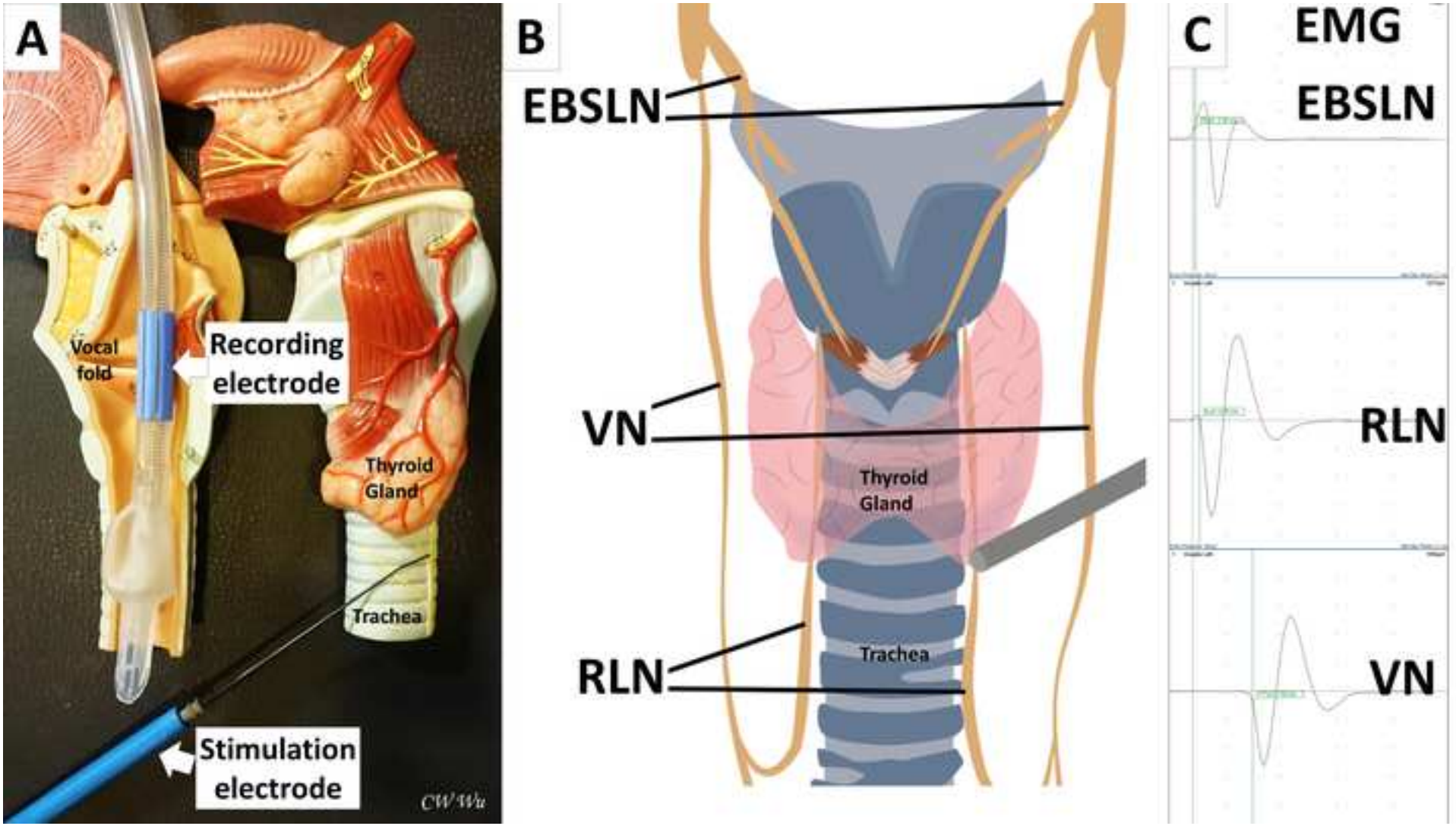

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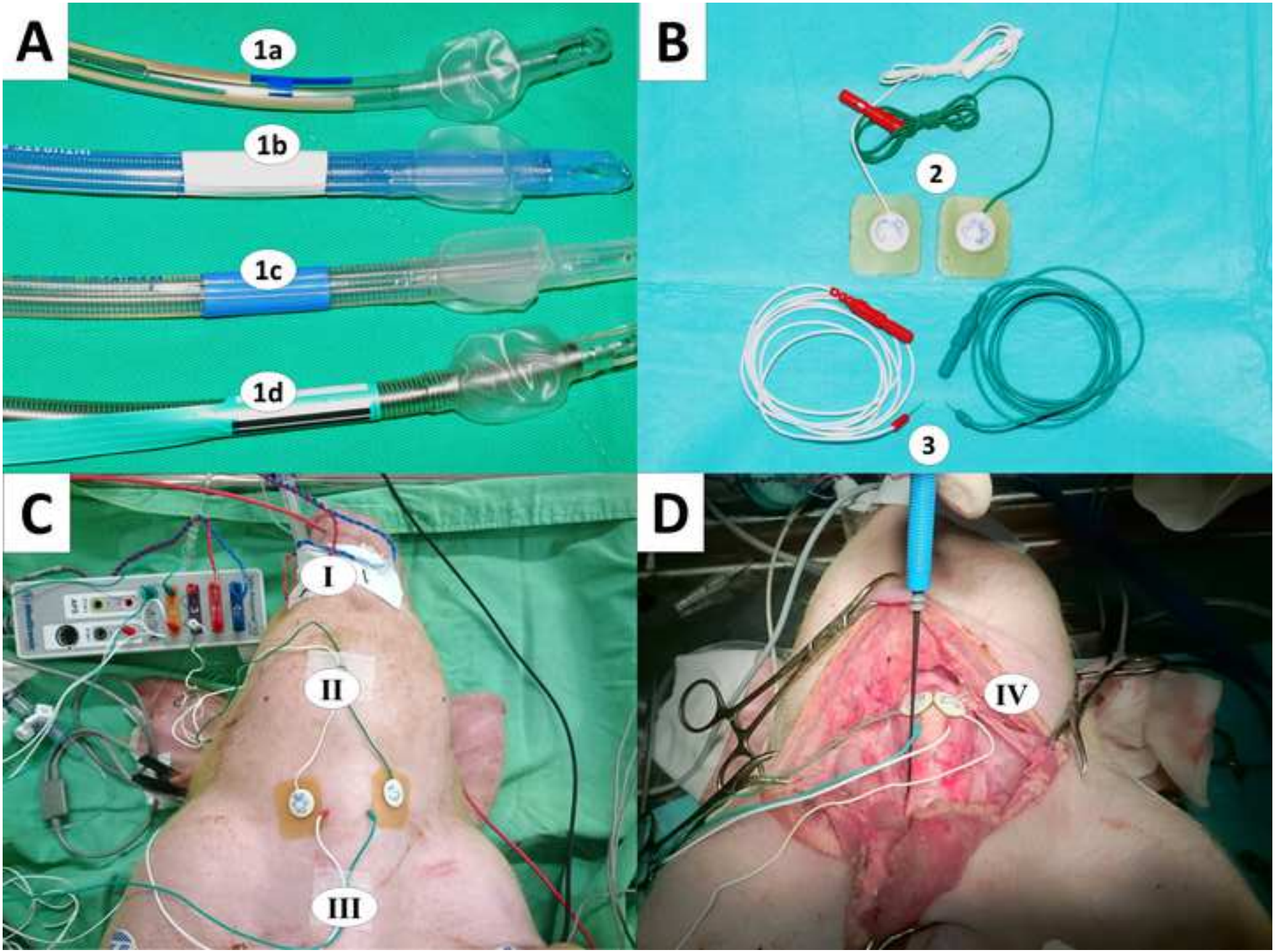

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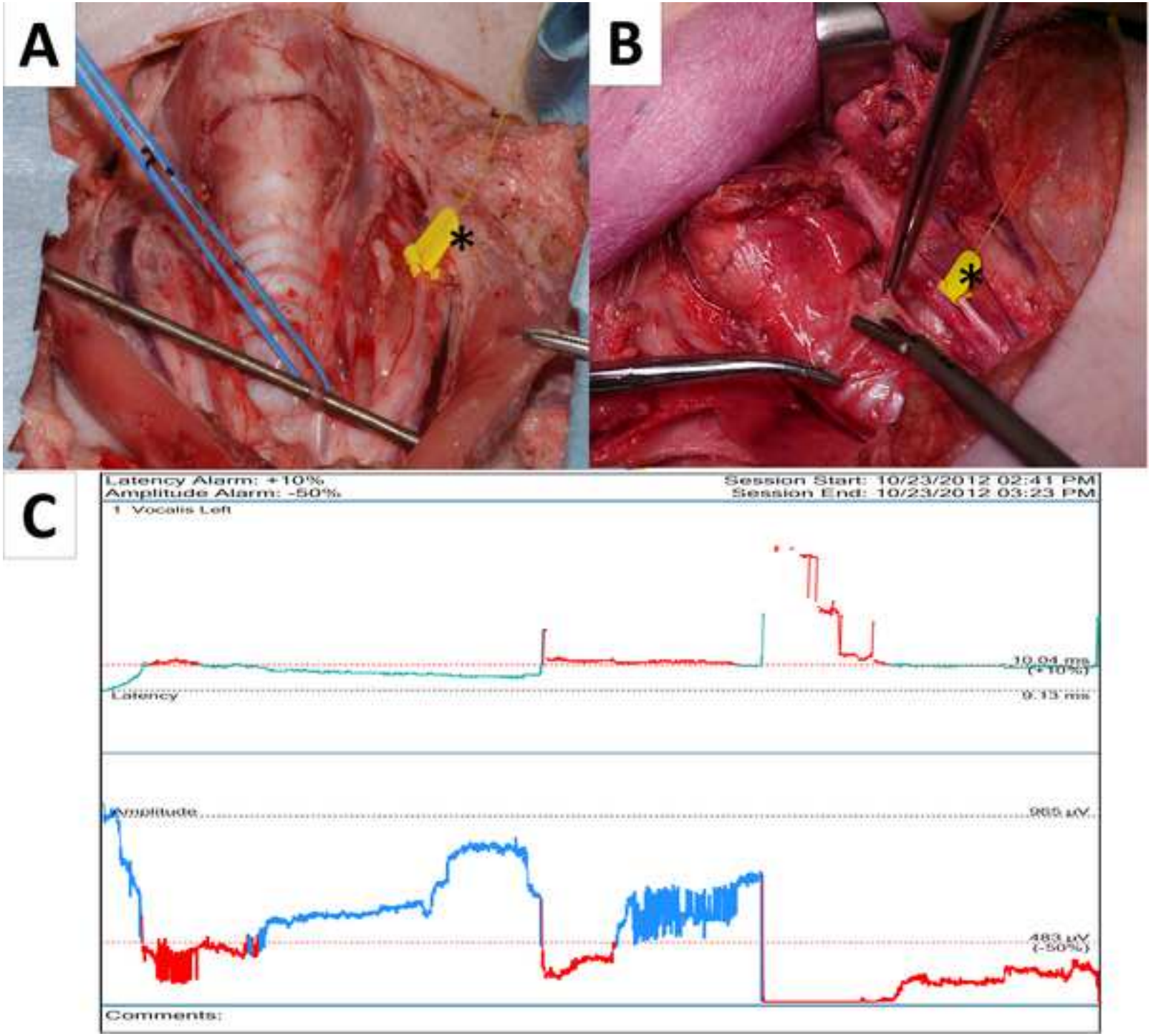

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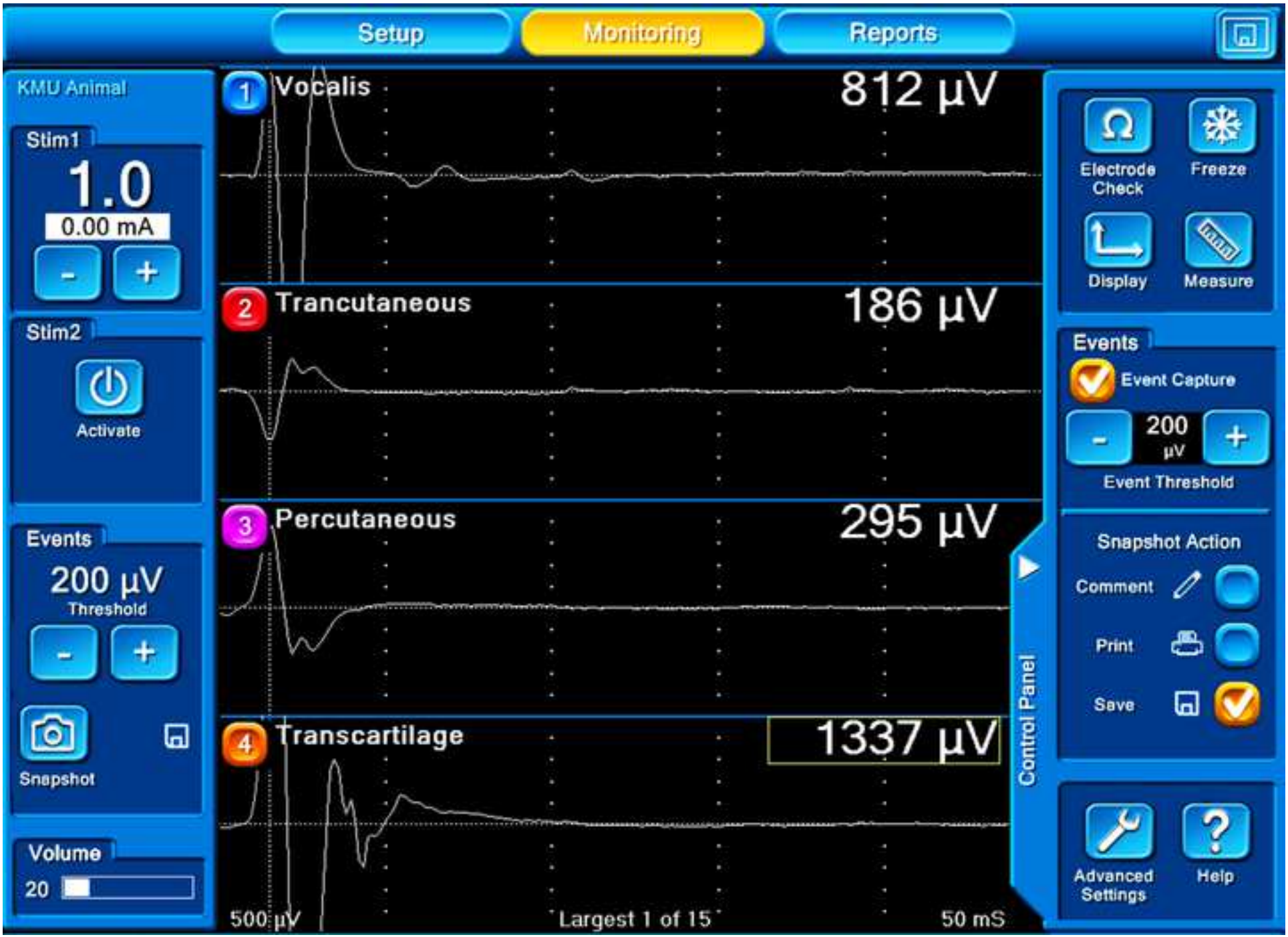

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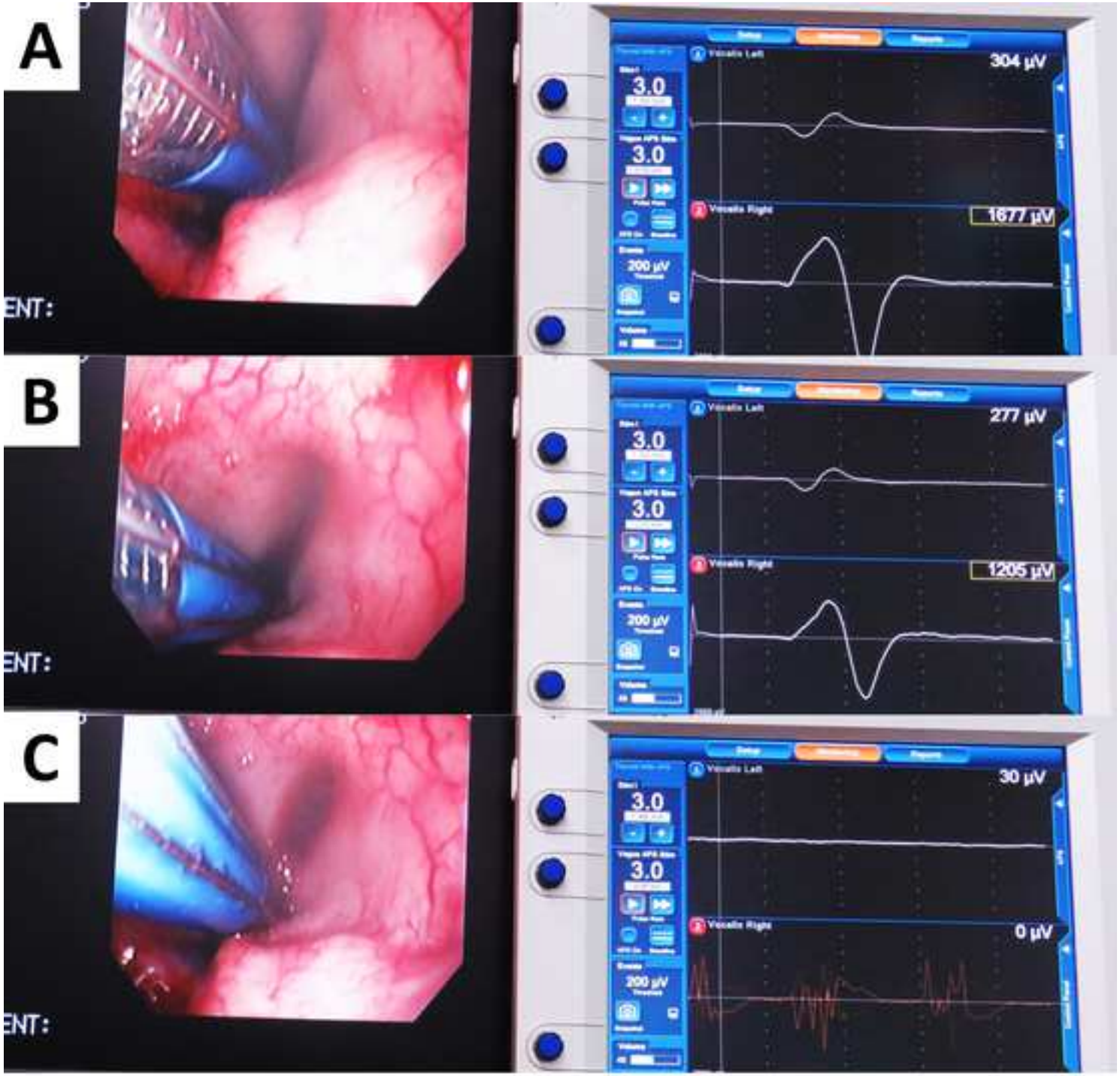

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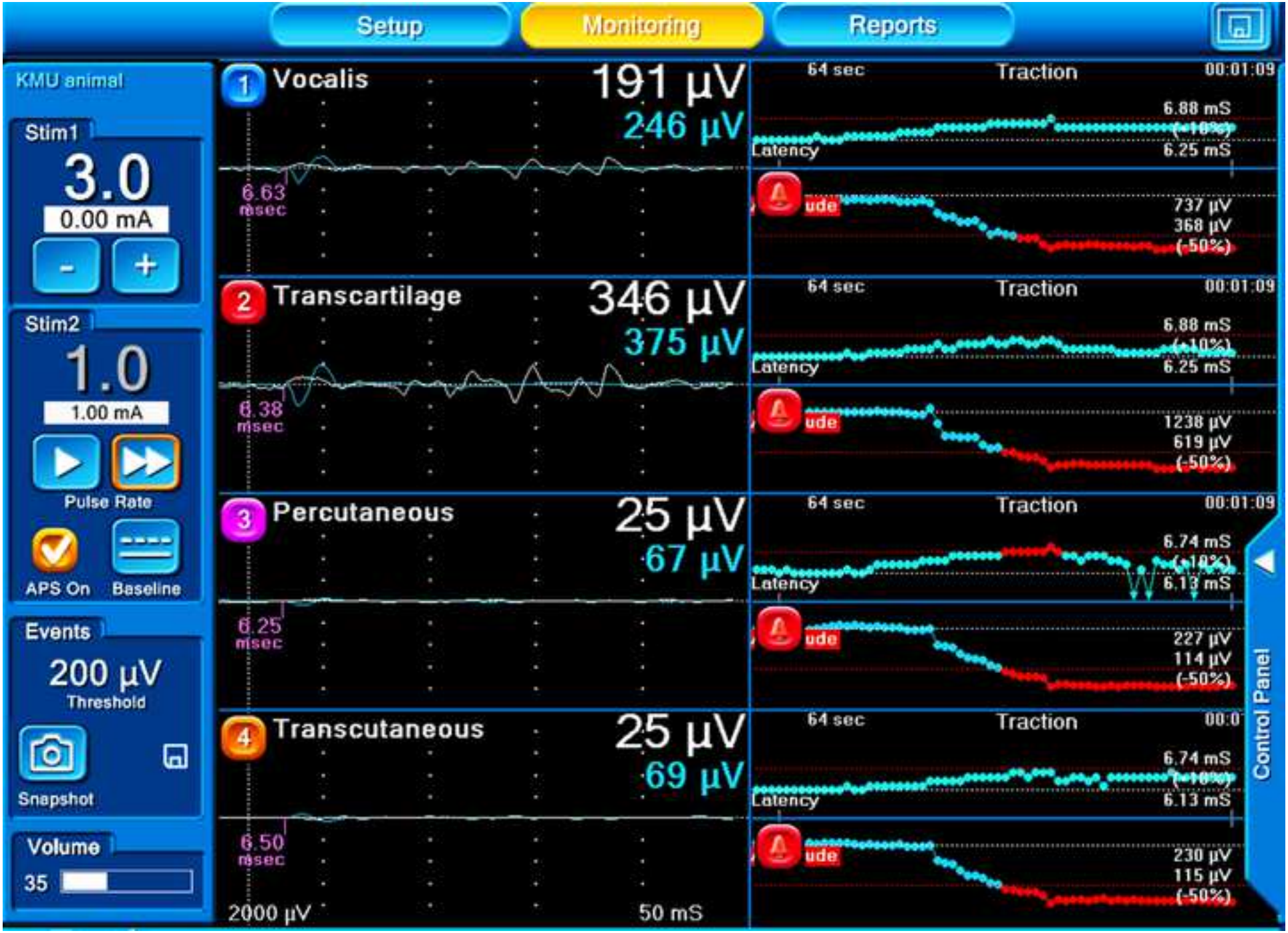

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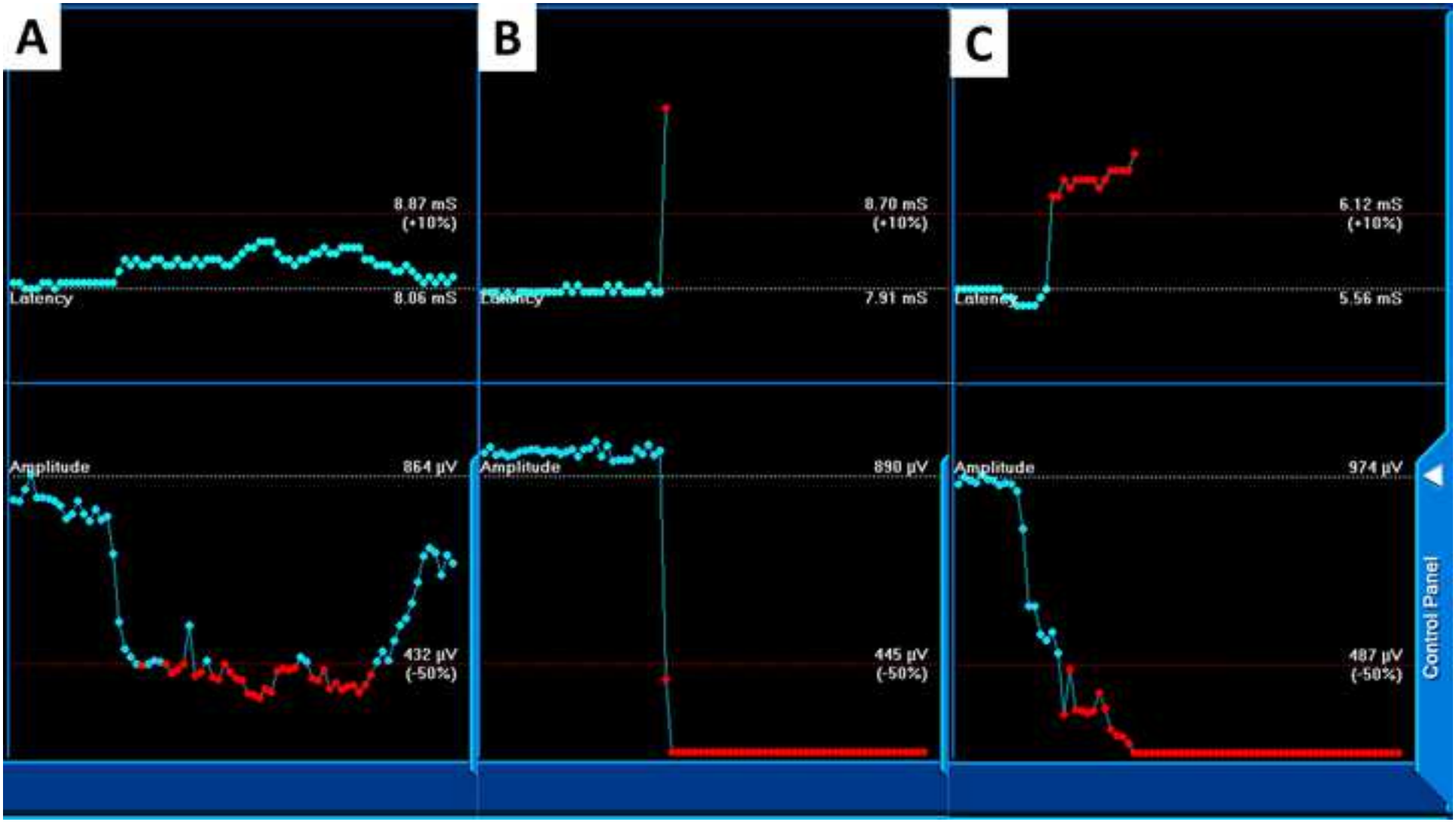

Table of Materials

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Name of Material/ Equipment	Company
Criticare systems	nGenuity™
Intraoperative NIM nerve monitoring s	Medtronic
NIM TriVantage® EMG Tube	Medtronic
NIM Contact® Reinforced EMG Endotr	Medtronic
NIM® Standard Reinforced EMG Endot	Medtronic
NIM Flex™ EMG Endotracheal Tube	Medtronic
Standard Prass Flush-Tip Monopolar St	Medtronic
Ball-Tip Monopolar Stimulator Probe	Medtronic
Yingling Flex Tip Monopolar Stimulato	Medtronic
Prass Bipolar Stimulator Probe	Medtronic
Concentric Bipolar Stimulator Probe	Medtronic
Side-by-Side Bipolar Stimulator Probe	Medtronic
APS™ (Automatic Periodic Stimulation	Medtronic
Neotrode® ECG Electrodes	ConMed
LigaSure Small Jaw	Medtronic

Catalog Number	Comments/Description
8100E	physiologic monitoring, including capnography, monitor EMG activity from
NIM-Response® 3.0	multiple muscles. If there is
8229706	6 mm ID, 8.2 mm OD. The NIM TriVantage® EMG
8229506	6 mm ID, 9 mm OD. The NIM Contact® EMG Tube
8229306	6 mm ID, 8.8 mm OD. The NIM Standard EMG Tube
8229960	6 mm. The NIM Flex EMG Tube monitors vocal cord
8225101	Tips and Handles. For locating and mapping cranial
8225275/ 8225276	Tip and Handle, 1.0 mm/ 2.3mm. Featuring a flexible
8225251	Tips and Handles. The highly flexible single-use Yingling
8225451	The single-use Prass Bipolar Stimulating Probe features a
8225351	The single-use Concentric Bipolar Stimulating Probe
8225401	The single-use Side-by-Side Bipolar Stimulating Probe
8228052 / 8228053	2 mm/ 3mm. The APS™ Electrode offers continuous,
1741C-003	The electrode is made of a clear tape material, which
LF1212	A FDA-approved electrothermal bipolar

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Article Title:	Porcine animal model for research of intra-operative neural monitoring in thyroid surgery
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Date:	2018-01-28

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Cover letter

Editor, ***The Journal of Visualized Experiments***

RE: Manuscript ID: JoVE57919R3 titled " Porcine Model in Intra-Operative Neural Monitoring in Thyroid Surgery "

Dear Editors,

Thank you very much for reviewing our article and providing useful advice. We have tried our best to incorporate your comments into the revised manuscript and feel that the changes you suggested make our manuscript clearer and more informative for the readers. All the important changes have been highlighted in the revised manuscript. With these modifications, we look forward to your re-review for possible publication in ***The Journal of Visualized Experiments***.

Sincerely,

I-Cheng Lu, MD, PhD (On behalf of all coauthors)
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June 12, 2018

The followings will respond to the points raised by the reviewer and the editorial office:

Response to the Editoral

Comments:

1. The language in the manuscript is not publication grade. Please employ professional copy-editing services.

Response: Thank you very much for this important comment. The revised manuscript has been reviewed and edited by a BELS-certified technical editor and native English speaker. We will agree to pay additional charges for further copy-editing service by the journal for the accepted paper, if necessary.

Paul Steve Lugue
14938 Camden Avenue Suite 39
San Jose, CA 95124
Tel: 408 916 1602
e-mail: steve@panoramixcorp.com

February 22, 2018

RE: Editing Certification

Dear Sir/Madam:

I am BELS-certified technical editor and native English speaker. This letter certifies that I edited the following manuscript, including language, grammar, punctuation, spelling, and style.

TITLE
Porcine model for research in intra-operative neural monitoring in thyroid surgery

AUTHORS & AFFILIATIONS
Che-Wei Wu[1], Tzu-Yen Huang[1], Hui-Chun Chen[2], Hsiu-Ya Chen[3], Tsung-Yi Tsai[1], Pi-Ying Chang[3], Yi-Chu Lin[1], Chiao-I Lin[1], Hsin-Yi Tseng[1], Pao-Chu Hun[4], Xiaoli Liu[5], Hui Sun[5], Gregory W. Randolph[5], Gianlorenzo Dionigi[6], Feng-Yu Chiang[1], and I-Cheng Lu[3]

The content and research findings were not changed in any way, and the authors reviewed the entire manuscript before its final submission. Please do not hesitate to contact me if you require further information.

Sincerely,

PS Lugue

Paul Steve Lugue
Technical Editor

2. Additional details are required in the protocol. Please see the comments in the attached manuscript.

Response:

Thank you very much. The protocol section has been revised accordingly.

3. The highlighting of the protocol is very discontinuous and does not tell a complete story. Please revise and ensure that only 2.75 page of protocol text is highlighted with the spaces and headers included.

Response:

Thank you very much. The highlighted protocol section has been revised as follows:

This study aims to develop a standard protocol of intra-operative neural monitoring of thyroid surgery in a porcine model. Here, we present a protocol to demonstrate general anesthesia, to compare different types of electrodes, and to investigate the electrophysiological characteristics of the normal and injured recurrent laryngeal nerves.

PROTOCOL-The animal experiments were approved by the IACUC of Kaohsiung Medical University, Taiwan.

1. Animal Preparation and Anesthesia

1.1. **Porcine animal model**

1.1.1. Use KHAPS Black or Duroc-Landrace pigs

1.2. **Anesthesia induction**

1.2.1. Pre-medicate with intramuscular azaperone (4 mg/kg) at 2 hours before anesthesia.

1.2.2. Induce general anesthesia with 2-4% sevoflurane at a fresh gas flow of 3 L/min *via* the face mask with the piglet in a prone position.

1.2.3. Identify a superficial vein on the outer side of one ear.

1.2.4. Administer intravenous anesthetic to alleviate noxious stimulation by direct laryngoscopy.

1.3. Tracheal intubation

1.3.1. Prepare the equipment required for EMG tube intubation: a face mask for assisted ventilation, two slings to hold the mouth open, one gauze strip to pull the tongue, a blunt tip suction catheter, a veterinary laryngoscope with straight blades, an elastic bougie, a syringe, a stethoscope, and adhesive tape.

1.3.2. Position the piglet in a prone position on the operating table.
1.3.3. apply traction of the upper and lower jaw to maintain an adequate mouth opening.
1.3.4. Hold the laryngoscope upside down and place it directly in the oral cavity to depress the tongue.
1.3.5. use the laryngoscope to press the epiglottis downward toward the tongue base.
1.3.6. When the vocal cords are clearly identified, gently advance the elastic bougie into the trachea. Next, advance the EMG tube at the mouth angle to a depth of 24 cm.
1.3.9 Use medical tape to fix the EMG tube at the mouth angle.
1.3.10. Connect the EMG tube to the ventilator.

1.4. Anesthesia maintenance

1.4.1. Maintain general anesthesia with 1-3% sevoflurane in oxygen at 2 L/min.

2. Equipment Setting and Animal Operation

2.1.1. Connect the channel leads from the EMG tube to the monitoring system.
2.1.2. Set the monitoring system to run 50 ms time window. Set pulsed stimuli to 100 μs and 4 Hz. Set the event capture threshold to 100 μV.
2.2.2. Use a transverse collar incision to expose the neck and the larynx.
2.2.3. Raise the subplatysmal flap.
2.2.4. Remove the strap muscles and visualize the tracheal rings and nerves.
2.2.5. Localize, identify, and carefully expose the EBSLN, RLN, and VN with a handheld stimulation probe.
2.2.6. Position an automated periodic stimulation electrode on one side of VN for continuous IONM.
2.3. At end of experiments, euthanize all piglets by the veterinarian.

3. Electrical Stimulation

3.1. Evaluate the baseline EMG responses of the target nerves.
3.2.3. During VN stimulation, evaluate hemodynamic stability by monitoring of heart rate, ECG, and invasive arterial blood pressure.
3.2.4. Evaluate nerve function integrity by comparing EMG responses proximal to the nerve stimulation site before and after each level of stimulation is applied.
3.3. Effect of anesthetics
3.3.1. Firstly, apply C-IONM and use the automatically calibrated baseline of EMG as control data.
3.3.2. Administer a bolus injection of rocuronium 0.3mg/kg and observe the real-time EMG changes.

3.3.3. Three minutes after injection, perform one injection of sugammadex 2mg/kg. Record the recovery profile of laryngeal EMG for 20 minutes.

3.4. Stimulation electrodes

3.4.1. To mimic direct stimulation of nerves during surgery, apply 1mA stimulation to the EBSLN, RLN, and VN without overlying fascia.

3.4.2. To mimic indirect mapping of the nerve position before visual identification during surgery, apply 1mA stimulation at a 1 and 2-mm distance away from the nerves at overlying fascia.

3.4.3. Record and compare the EMG responses between different types of stimulation electrodes.

3.5. Recording electrodes

3.5.1. evaluate how rotation or displacement of the EMG tube electrode affects the stability of the EMG signal. Additionally, compare the EMG responses between different electrode types and different recording approaches during IONM.

4. RLN injury study

4.2. Use C-IONM to confirm and compare patterns of real-time changes in evoked laryngeal EMG signals during and after acute RLN injuries with different injury mechanisms

4.4. Traction compression injury

Wrap a vascular loop around the RLN and apply retraction. This scheme mimics an RLN trapped at the region of Berry's ligament during medial traction.

4.5. Clamping injury

pinch the distal segment of the RLN with hemostatic forceps for one second. This scheme mimics the nerve being inadvertently clamped owing to visual misidentification as a vessel during the operation.

4.6. Thermal injury

4.6.2. Activation Study - To investigate how Energy-based devices (EBD) can be safely applied for hemostasis and dissection near the RLN during surgery.

4.6.2.1. Activate the EBD at 5-mm distance away from the RLN.

4.6.2.2. If EMG signals remain stable, perform a further test at the narrower distance.

4.6.3. Cooling Study- To evaluate the cooling time to determine postactivation optimal EBD cooling parameters.

4.6.3.1. Contact an activated EBD on the RLN directly after a 5 second cooling time.

4.6.3.2. If the EMG signals remain stable after three tests, test the shorter cooling time.

Summary of the highlighted protocol text for the inclusion in the video:

Porcine Model in Intra-Operative Neural Monitoring in Thyroid Surgery

This study aims to develop a standard protocol of intra-operative neural monitoring of thyroid surgery in a porcine model. Here, we present a protocol to demonstrate general anesthesia, to compare different types of electrodes, and to investigate the electrophysiological characteristics of the normal and injured recurrent laryngeal nerves.

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