Original article

Experimental study of needle recording electrodes placed on the thyroid cartilage for neuromonitoring during thyroid surgery

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Background: **Needle electrodes placed on the thyroid cartilage (TC) are an alternative to endotracheal tube (ET) electrodes for assessing recurrent laryngeal nerve (RLN) function during thyroid surgery. Needle electrodes placed on the TC were evaluated in an experimental porcine model.**

Methods: **Continuous intraoperative neuromonitoring was used to record the electromyogram. Each TC side was delineated into nine areas to determine the optimal placement of the electrode, and needle electrode area, depth and orientation for optimal electromyographic (EMG) amplitudes were evaluated. RLN root locations were stimulated at four locations: vagus nerve distal to the neuromonitoring electrode, and most proximal, middle and laryngeal entry points of the nerve. A nerve retraction injury model was adapted to compare RLN monitoring by TC *versus* ET electrodes.**

Results: **An optimal site for placement of needle electrodes was identified, and electromyograms obtained from the various needle insertion depths and orientations were similar. Latencies recorded from the TC and ET electrodes were similar. The amplitude profile of TC electrodes responded earlier to RLN injury than that of ET electrodes. Amplitude and drop to loss of signal were also registered earlier.**

Conclusion: **EMG amplitudes obtained using TC electrodes were higher, and identified RLN injury earlier than ET electrodes.**

Surgical relevance

Needle electrodes placed on the thyroid cartilage (TC) are an alternative to endotracheal tube (ET) electrodes for assessing the function of the recurrent laryngeal nerve (RLN) in thyroid surgery.

This study used an experimental porcine model to evaluate the use of needle electrodes inserted in the TC, compared with ET electrodes, for producing an electromyographic (EMG) profile of the RLN. Nine areas of the TC, with various needle insertion depths and orientations, were compared. Perichondral insertion into the avascular area of the TC was found to be safe. The EMG amplitude and latency features recorded via the TC and ET electrodes were compared, using both intermittent and continuous monitoring. Changes in EMG amplitudes in response to nerve traction injury were registered earlier with TC electrodes than with ET electrodes, and the amplitudes were higher and more stable. Latencies obtained via the TC and ET electrodes were similar.

These results indicate that the development of a non-invasive monitoring electrode with improved function, easy placement and low cost is possible.

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Introduction

Several methods have been proposed for monitoring the recurrent laryngeal nerve (RLN) during thyroid and parathyroid surgery. These include laryngeal palpation, glottic observation or pressure recording, endoscopic placement of intramuscular electrodes on the vocal cord or through the cricothyroid membrane, and use of postcricoid or electromyographic (EMG) endotracheal tube (ET)-based surface electrodes[1]. For reasons of safety and simplicity, the most common intraoperative neuromonitoring (IONM) systems currently rely on ET surface electrodes[1−3]. ET surface electrodes are designed for placement at the level of the glottis, with the endotracheal cuff in its normal position in the subglottis. The electrodes then make contact with the medial surface of the vocal cords, for monitoring the summed depolarization of the bilateral vocalis portions of the thyroarytenoid muscles[3−5].

Despite the many advantages of ET electrodes, there are also problems in terms of verification, maintenance, stability, patient selection and operative use (*Table S1*, supporting information)[1−7]. Proper placement of the ET with complete contact with the mucosa of the vocal cords is essential to minimize monitoring problems, specifically to obtain the best impedance, thus providing a precise EMG profile and exact determination of loss of signal, and allowing differentiation between signal and artefact[1−6]. A poor and unreliable signal can be due to improper outer diameter of tube, malposition, degree of rotation, depth of insertion, upward or downward displacement, salivary pooling, tube fixation, or change in head and tracheal position[8]. Furthermore, an error in intraoperative RLN stimulation is possible if there is interference owing to transtracheal stimulation, in which current is shunted to the ET electrodes, especially in a situation where the RLN is adjacent to the trachea/ET electrodes[1].

Methods to assess the position of the ET include repeat laryngoscopy, respiratory variation, checking impedance values and a tap test[1,2]. However, even with great attention to initial tube positioning, corrective manoeuvres are required in 5–7 per cent of monitored thyroid operations. These necessitate additional procedures, and their accuracy in determining the proper position of the ET has not been evaluated[1−6,8].

Obtaining EMG data via ET electrodes is especially challenging in the case of tracheal invasion, resection, tracheostomies or giant goitres[1,2], and ET electrodes also increase total costs[9]. Standard ETs can be converted to monitoring tubes by attaching an adhesive pad with paired electrodes, so that the lower electrode is 7–10 mm above the upper edge of the tube cuff[1], but care must be taken to ensure that the adhesive pad electrode adheres closely to the ET and does not overlap with itself[9].

Alternatively, the functions of the thyroarytenoid muscle and RLN may be assessed using needle electrodes placed into the thyroid cartilage (TC). Chiang and colleagues[2] and Van Slycke *et al.*[8] showed that TC electrodes are an alternative IONM format for recording laryngeal EMG signals during thyroidectomy. This experimental study assessed the feasibility of using needle electrodes in the TC at various locations, depths and orientations to obtain an EMG signal profile of the RLN, and evaluated TC electrodes relative to ET electrodes for EMG performance.

Methods

Four female Meishan piglets were obtained from the Laboratory Animal Centre of Jilin University (mean(s.d.) age 1·5(0·3) months; weight 24·1(1·6) (range 22·8–25·9) kg). The Animal Care and Use Committee of Jilin University approved this study, which was conducted in accordance with ARRIVE guidelines[10].

Induction and maintenance of anaesthesia

Induction anaesthesia comprised 0·5 mg atropine sulphate via subcutaneous injection, and intramuscular administration of 40 mg (2 mg/kg) each of tiletamine/zolazepam and xylazine hydrochloride. An EMG surface ET electrode (standard reinforced 7·0#; Medtronic, Jacksonville, Florida, USA) was secured tightly. The depth and angle of contact between the ET electrode surface and the mucosa of the vocal cord were confirmed by video laryngoscopy[1]. Use of muscle relaxants was avoided[1]. Isoflurane (2·0–3·0 per cent) and oxygen (2·0 l/min) were used to maintain general anaesthesia[1].

Intraoperative neural monitoring equipment

NIM® Nerve Monitoring System 3·0 (Medtronic) software was used to record the electromyogram. The event threshold was set at 100 μV[1]. Nerves were stimulated with a single-use, incrementing Prass® stimulating probe (no. 8225490; Medtronic), with an impulse duration of 100 ms and frequency of 4 Hz. Real-time EMG data were obtained via continuous vagus nerve stimulation using a 2·0-mm Automatic Periodic Stimulation (APS®) electrode (Medtronic)[11]. The amplitude and latency waveforms were displayed separately, and the upper limit threshold for the latency (+10 per cent) and lower limit threshold for amplitude (−50 per cent) were depicted as separate alarm lines[1,11]. Loss of signal was assumed in the event of signal failure or an EMG signal below 100 μV with a primary intact signal and adequate stimulation of 1–2 mA[1]. Needle recording electrodes 12 mm in length were used (Medtronic Xomed, Jacksonville, Florida, USA). The electrodes were made from a composite of stainless steel and a platinum/iridium alloy[12−15].

Experimental set-up and evaluations

To determine TC areas that were suitable for insertion of a 2-mm long needle tip so that it would not penetrate through to the inner tissues of the larynx, the thickness of the TC was measured before surgery using a portable colour Doppler ultrasonography machine (S8 Series, Sonoscape; Shenzhen, China) with the animal supine and the neck extended (*Fig. S1*, supporting information). The thickness of the TC was determined after operation with callipers (Sheffield®; Great Star, Hangzhou, China). The thickest and thinnest parts of the TC on both sides were in the lower lateral and middle portions respectively.

After surgical disinfection, an H-shaped incision was made in the middle of the neck to expose the thyroid, carotid sheet and TC. The TC anatomy was outlined, length and width, on each side. Each side of the TC was then delineated and marked into nine areas by two transverse and two sagittal lines (*Fig. 1a,c*). The APS® electrodes were implanted bilaterally. The RLN root was stimulated at the following locations: vagus nerve just distal to the APS® electrode position (a); most proximal segment of the RLN (b); middle portion of the RLN (c); and the RLN at the laryngeal point of entry (d) (*Fig. 1b*). The latencies of the EMG recordings via the TC and ET electrodes were compared.

Apart from comparison of latencies, the following general features of TC electrode placement and the resulting EMG profiles of the RLN were assessed: influence of the TC anatomy on the recording; associations between EMG values and area of needle insertion; associations between the EMG profile and depth of needle insertion; associations between the EMG signal and needle orientation; detection and confirmation of RLN monitoring by TC and ET electrodes via nerve retraction; and effect of manipulation of the trachea on EMG amplitude and latency.

Associations between electromyographic values and area of needle insertion

The needle electrode tips were adjusted with rigid plastic tubing to ensure an insertion depth of 2 mm (*Fig. 1d*). The needle electrodes were inserted sagittally and into the centre of each of the nine delineated areas in the TC. The EMG parameter values from both the TC and ET electrodes were recorded simultaneously. The optimal TC electrode placement area was defined as the area with the highest EMG signals.

Associations between electromyographic profile and depth of needle insertion

The optimal depth of insertion of the TC electrodes was defined as the depth at which the highest EMG signals were recorded. To determine this, the lengths of the exposed portion of the needle electrodes were adjusted to 2, 5 or 12 mm (entire length) with plastic tubing (*Fig. 1e*). The needle electrodes were inserted sagittally and centrally in each bilateral TC area, and EMG recordings made (*Fig. 1f*).

Associations between electromyographic signal and needle orientation

To determine the optimal orientation of the needle when inserted in each area of the TC, the direction of insertion was labelled according to the hands of an analogue clock around the centre of each area (*Fig. S2*, supporting information). Thus, the needle was inserted in the centre and subsequently pointed in 12 different directions, corresponding to each hour of the clock. EMG recordings were taken at each position. The optimal direction was considered that which obtained the highest EMG signals.

RLN monitoring during retraction

To detect and confirm RLN monitoring by the TC needle electrodes, a nerve traction injury model, as described by Wu and colleagues[11], was used (*Fig. 2a*). Briefly, the RLN was dissected and a 1·5-mm wide vascular rubber loop was positioned around the nerve and retracted slowly. EMG parameters were recorded by both TC and ET electrodes, with the TC electrode in the optimal position. The traction was held until the alarm of the continuous IONM equipment sounded, at which point the traction was stopped, with standby until recovery of the electomyogram. Finally, traction of the RLN was implemented until loss of signal.

Response of electromyographic amplitude and latency to manipulation of the trachea or RLN retraction

To determine whether manipulation of the trachea influenced the EMG recordings, the trachea was gently pushed or pulled towards or away from the operator on each side, and changes in the recordings during this process were recorded.

Statistical analysis

All data are reported as mean(s.d.). Multiple group comparisons were done using one-way ANOVA. Two-group comparisons were performed using Student's t test. $P < 0{\cdot}050$ was considered statistically significant. Statistical analyses were carried out using SPSS® version 22 for Windows® (IBM, Armonk, New York, USA).

Results

Measurement of thyroid cartilage thickness and width

On preoperative ultrasonography, the mean(s.d.) thickness of the TC was 2·75(0·75) (range 1·8–4·1) mm on

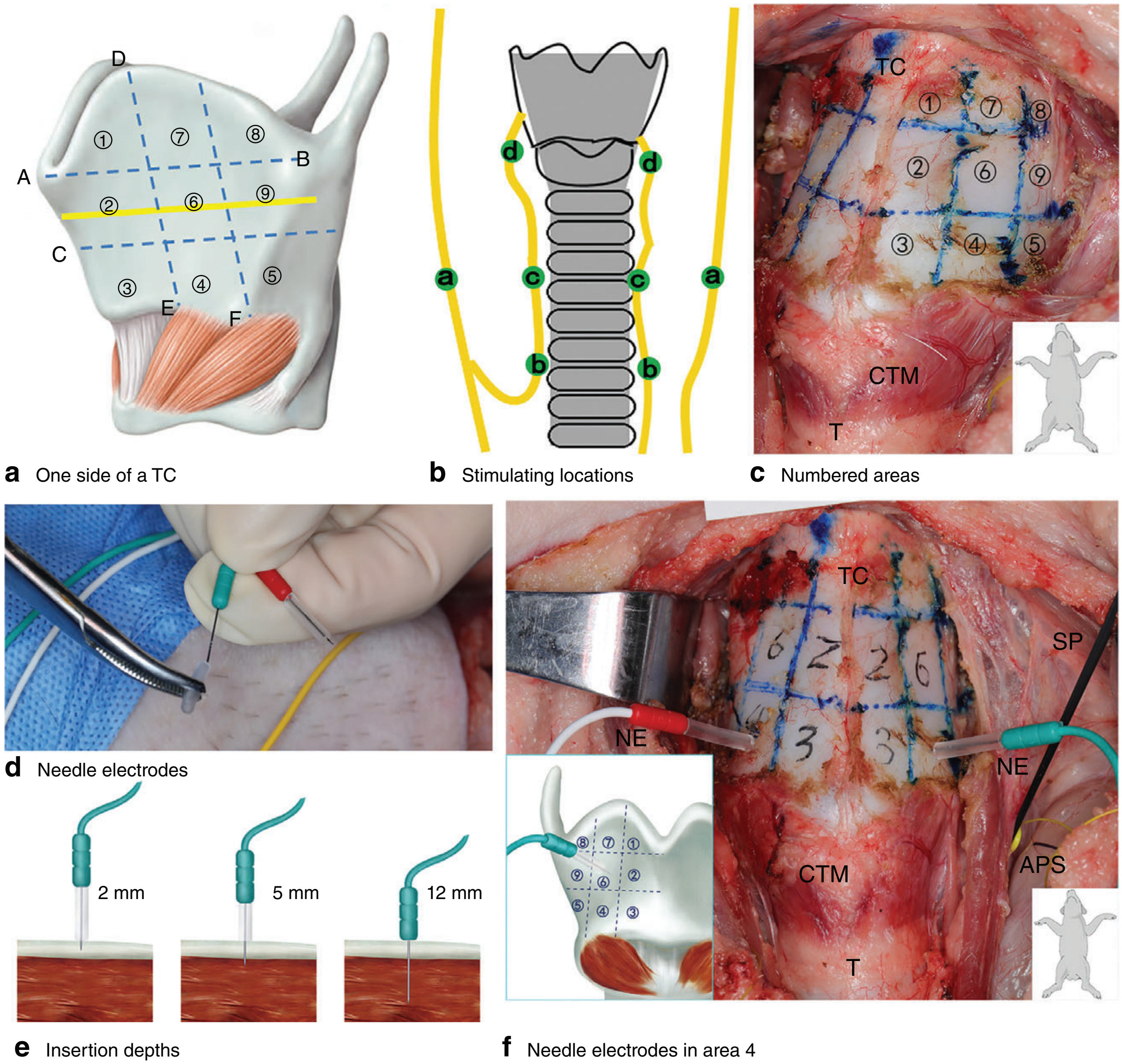

Fig. 1 Each thyroid cartilage (TC) side was divided into nine numbered areas, each occupying 1 cm^2. Only areas 1–6 were evaluated in this study; areas 7–9 were excluded owing to intrinsic difficulties in placing needles. **a** Schematic illustration of one side of a TC. The most cranial transverse line extended from the prominentia laryngea (A) to the superior tubercle (B), and divided the anterior horn into upper and lower parts. The most caudal transverse line was at the middle level of the lower part of anterior TC horn (C). Two parallel lines were drawn perpendicular to the transverse lines, and were also parallel to the anterior horn of the TC. The medial line (D to E) started at the medial margin of the rectus division of the cricothyroid muscle (E); the lateral line started at the medial margin of the obliquus division of the cricothyroid muscle (F). **b** Schematic illustration of the four stimulating locations (a–d) on the recurrent laryngeal nerve. **c** Intraoperative view of the nine numbered areas. **d** Intraoperative view of needle electrodes. The insertion depth of the exposed needle electrodes was adjusted according to the thickness of the TC, by cutting rigid plastic tubing shorter than the needle. **e** Schematic illustration of needle electrodes with different depths inserted into the TC. **f** Intraoperative view of recording needle electrodes inserted 2 mm into TC area 4; inset shows an illustration of needle electrodes inserted into the TC. APS, APS® electrode; CTM, cricothyroid muscle; NE, needle electrode; SP, stimulation probe; T, trachea

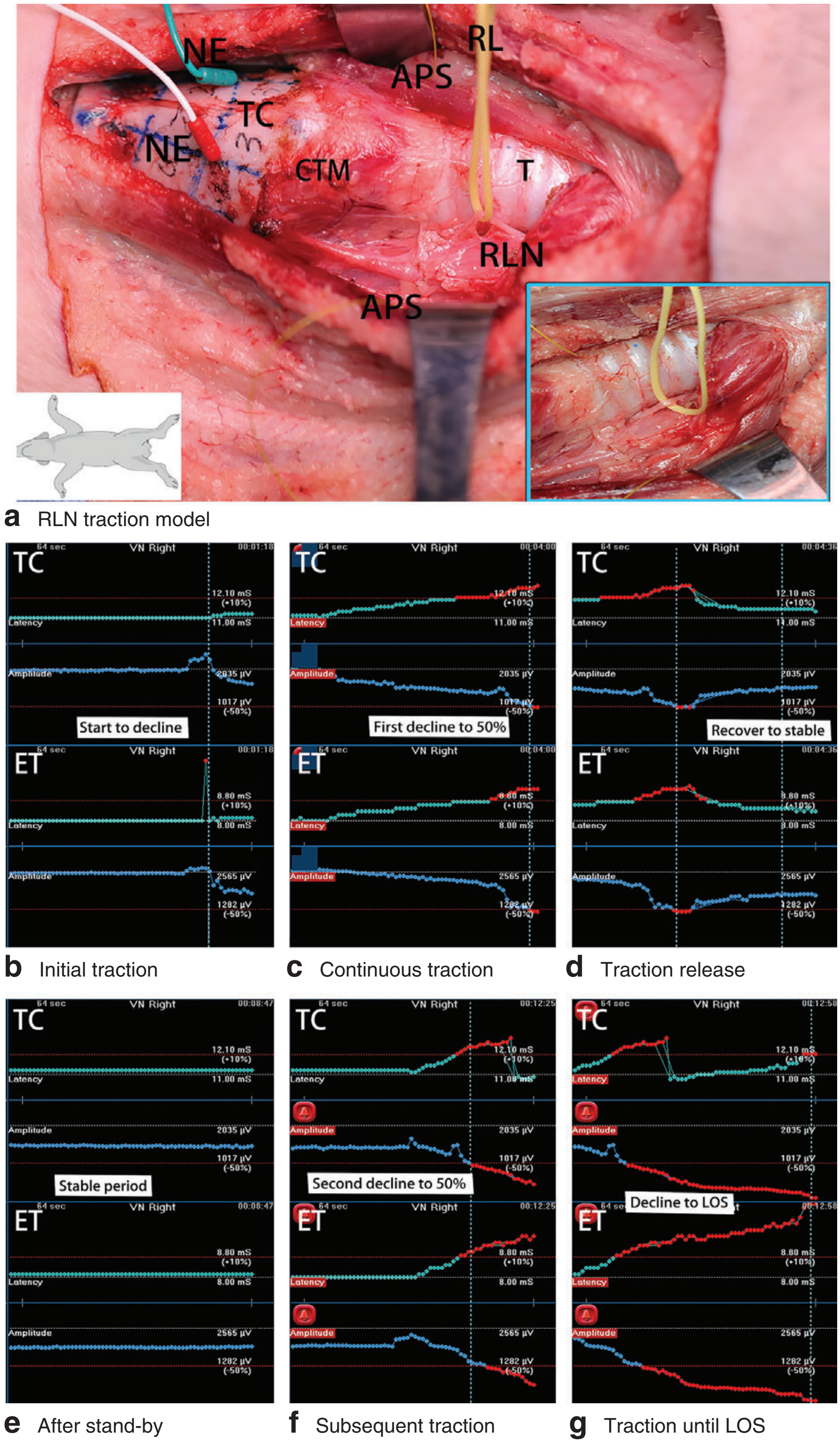

Fig. 2 Legend on next page.

Table 1 Amplitudes of thyroid cartilage and endotracheal tube electrodes by thyroid cartilage area and depth of electrode insertion

		Amplitude (μV)					
Depth (mm)	Electrode	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
2	ET	1705(315)	1694(230)	1661(255)	1591(356)	1618(276)	1576(370)
	TC	270(45)	412(89)	599(124)	2264(400)	2398(386)	1688(761)
	TC/ET	0·16	0·24	0·36	1·42	1·50	1·07
5	ET	–	–	–	1587(385)	–	1584(316)
	TC	–	–	–	2537(540)	–	2372(1096)
	TC/ET	–	–	–	1·60	–	1·50
12	ET	–	–	–	1596(339)	–	1422(318)
	TC	–	–	–	2641(1263)	–	1782(987)
	TC/ET	–	–	–	1·65	–	1·25

Values are mean(s.d.). ET, endotracheal tube; TC, thyroid cartilage.

the left side and 2·65(0·71) (1·5–3·6) mm on the right. The postoperative calliper measurements were 2·42(0·82) (1·51–4·21) and 2·50(0·76) (1·59–4·30) mm respectively. There were no significant differences between the preoperative and postoperative measurements in terms of thickness of the left and right sides of the TC ($P = 0·512$).

The thickness of the nine delineated areas of the TC was also determined using callipers (*Fig. S1*, supporting information). Areas 7, 8 and 9 were too thick for viable recording, and were not used further in this study. The thickness of areas 1–6 was 1·82(0·16), 1·88(0·30), 2·29(0·26), 3·53(0·66), 3·31(0·26) and 1·95(0·29) mm respectively. The thickness of the suitable areas of the TC (areas 1–6) ranged from 1·8 to 3·5 mm.

The width of the left and right sides of the TC was 33·50(1·91) (range 32–36) and 31·75(2·36) (30–35) mm respectively, and the length was 43·50(6·25) (36–50) and 43·25(6·65) (35–50) mm, measured using a calliper after surgery.

Associations between electromyographic values and area of needle insertion

EMG values recorded by TC electrodes were higher in areas 4–6 than in areas 1–3 (*Table 1* and *Fig. 3a*). Amplitudes recorded by TC electrodes in areas 4 and 5 were significantly higher than those recorded by ET electrodes ($P < 0·001$), whereas amplitudes measured by TC and ET electrodes in area 6 were similar ($P = 0·713$). There was no difference in latency between TC and ET electrodes.

Associations between electromyographic profile and depth of needle insertion

The EMG profiles that resulted from TC needles being inserted at 2, 5 or 12 mm were not significantly different (*Table 1* and *Fig. 3b*). The latencies for TC and ET electrodes were also similar. It became clear that placing the needle in area 5 at the edge of the TC was difficult. This area is deep in the neck, with the cartilage close to the surrounding muscle, and the needle was unstable when placed in the sagittal position.

Associations between electromyographic signal and needle orientation

The test to determine the optimal needle orientation revealed no significant difference between the 12 positions ($P = 0·837$). In each of the 12 positions, the EMG amplitudes recorded by TC electrodes were greater than those recorded by ET electrodes (*Fig. 3c*); the ratio of TC to ET amplitudes ranged from 1·17 (4 o'clock) to 1·43 (10 o'clock). The latencies of TC and ET electrodes were comparable at each orientation.

Fig. 2 Recurrent layryngeal nerve (RLN) monitoring by traction experiment. **a** Thyroid cartilage (TC) electrodes were placed according to the optimal method (area 4) and the RLN was retracted; inset shows enlarged detail of the RLN. **b–g** Representative amplitude and latency profiles of the TC and endotracheal tube (ET) electrodes during the RLN traction experiment. **b** Initial traction of RLN; the amplitude began to decline. **c** Continuous RLN traction; the amplitude declined and the latency increased gradually. **d** RLN traction release; the amplitude and latency recovered and gradually stabilized. **e** After 4 min of stand-by, the amplitude and latency recovered to baseline levels. **f** Subsequent RLN traction; the amplitude again declined to 50 per cent of baseline. The amplitude from the TC electrodes declined earlier than that from the ET electrodes. **g** RLN traction until loss of signal (LOS). APS, APS® electrode; CTM, cricothyroid muscle; NE, needle electrode; RL, rubber loop (yellow); T, trachea

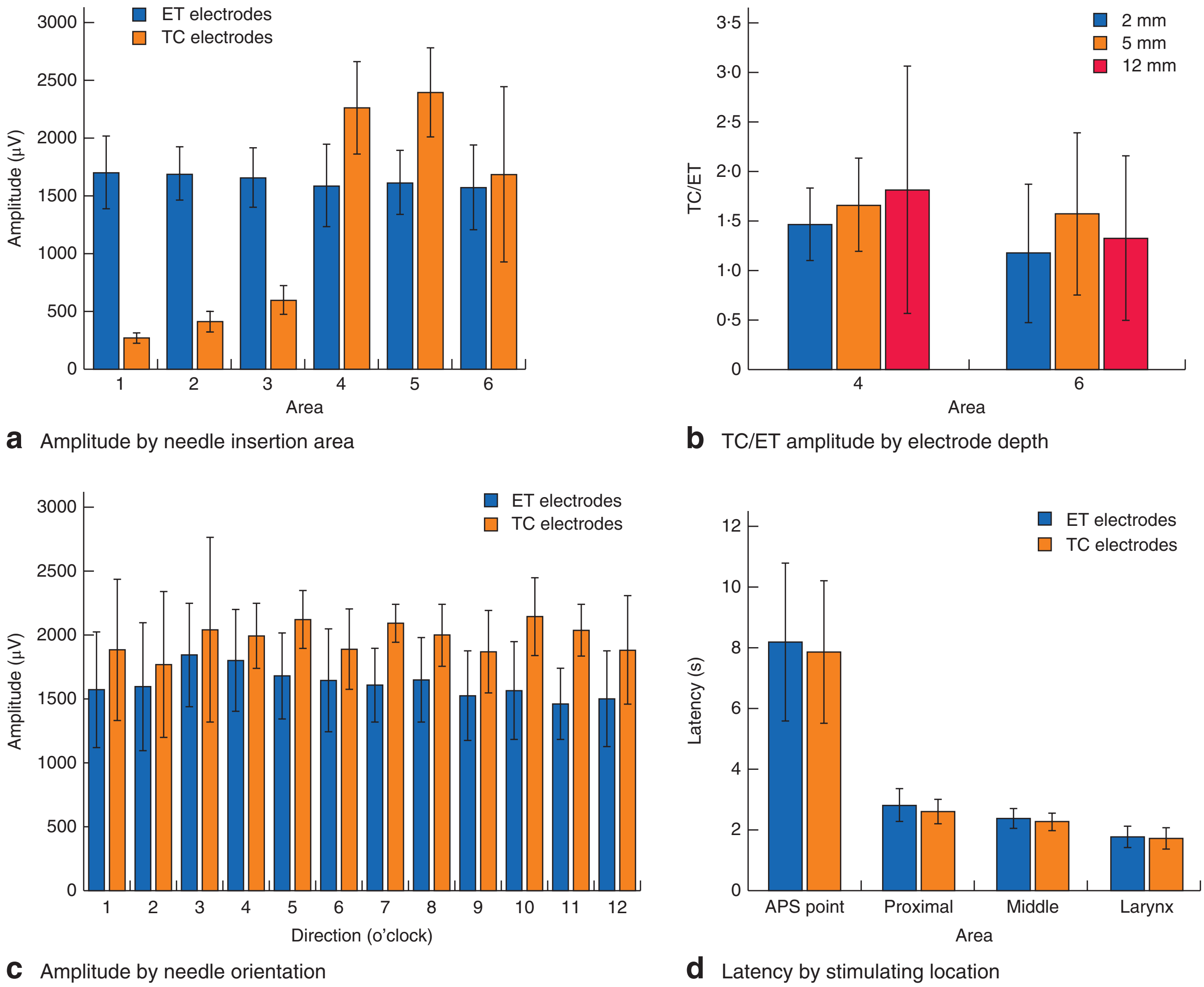

Fig. 3 **a** Association between electromyographic (EMG) amplitudes and needle insertion area of endotracheal tube (ET) and thyroid cartilage (TC) electrodes. **b** Ratio of TC to ET EMG amplitudes in TC areas 4 and 6, by electrode needle insertion depth. **c** Amplitude and needle orientation in TC area 4. **d** Latency recorded from TC and ET electrodes in TC area 4 with different stimulating locations. Values are mean(s.d.). APS, APS® electrode

Latency recorded by thyroid cartilage electrodes *versus* endotracheal tube electrodes

There were no significant differences in the latency of EMG recordings between ET and TC electrodes. The mean latencies of TC electrodes were similar to those of ET electrodes at all four stimulation points (*Fig. 3d*).

RLN monitoring during retraction

In the nerve traction injury model (*Fig. 2*), both TC and ET electrodes received the EMG signal from the APS®. TC electrodes recorded the modified amplitude profile earlier than did ET surface electrodes. Specifically, the initial decline, decrease to 50 per cent of the baseline value and recovery of the amplitude of TC electrodes were earlier by a mean of 0·38(0·92), 0·88(1·25) and 3·88(1·89) s respectively compared with those for ET electrodes. When testing for loss of signal, the amplitude drop of TC electrodes was 5·25(1·98) s earlier than that of ET electrodes (*Table 2*).

Response of electromyographic amplitude and latency to manipulation of the trachea or RLN retraction

Manipulation of the trachea (*Fig. S3a*, supporting information) and traction of the RLN (*Fig. S3b*, supporting

Table 2 Time of electomyographic amplitude changes registered by thyroid cartilage electrodes relative to endotracheal tube electrodes in the recurrent laryngeal nerve traction injury model

		Difference in time between TC and ET electrodes (s)				
		First retraction			Second retraction	
	Side	Start of decline	Decline to 50%	Recovery	Decline to 50%	Decline to LOS
Pig 1	Left	0	1	−1	−4	0
	Right	−1	−1	−4	−8	0
Pig 2	Left	0	−2	−7	−3	1
	Right	−1	0	−5	−5	2
Pig 3	Left	0	−1	−2	−6	−2
	Right	0	−3	−5	−5	1
Pig 4	Left	1	0	−3	−8	1
	Right	−2	−1	−4	−3	−1
Mean(s.d.)		−0·38(0·92)	−0·88(1·25)	−3·88(1·89)	−5·25(1·98)	0·25(1·28)

TC, thyroid cartilage; ET, endotracheal tube; LOS, loss of signal.

information) both affected EMG amplitudes recorded by the ET electrode.

Discussion

This study assessed the feasibility of using needle electrodes in the TC to obtain an EMG signal profile of the RLN during thyroid surgery, and evaluated TC electrodes relative to ET electrodes for EMG performance. A porcine model was used to determine whether anatomical dimensions of the cartilage influenced the TC recordings. Moreover, the optimal area for recording, and the best insertion depth and orientation of the needle in terms of the highest EMG amplitude were estimated. Recording from the TC was not affected by the anatomical TC dimensions. Although the recorded amplitude was highest in TC area 4, the depth of electrode needle insertion or needle orientation had no significant effect. TC electrodes registered changes in amplitude more quickly and to a greater degree in response to RLN traction events compared with ET electrodes, whereas the latencies were similar.

TC needle electrodes delivered larger-amplitude values during IONM, and more stable EMG signals during tracheal manipulation, than ET electrodes. Higher amplitudes at the beginning of thyroid surgery are considered helpful for the entire monitoring process, being a prerequisite for the evaluation of quantitative changes and surgical strategy, and prediction of postoperative vocal cord function[1,5,16]. In addition, stable EMG parameters are important for estimating nerve function during surgery, especially during thyroid surgery with continuous IONM, and stability is important to provide a reference in case of alarming events or loss of signal. When ET surface electrodes are used, significant alterations in EMG amplitude can occur owing to tube malposition alone, leading to false-positive results[2–5,17].

In the present model of RLN retraction injury, TC electrodes detected the adverse event of amplitude decline earlier than did ET electrodes. Theoretically, the recordings of TC electrodes and ET electrodes should be the same, and therefore these results are notable. Interestingly, Fujimoto and Nishizono[18] also observed different rise times when recording muscle contractile properties using surface electrodes and needle electrodes. The difference may be due to different receiving sites or contacts between the electrodes and muscles, which lead to different distances between main-effect muscles and the recording electrodes. Although no similar previous study has addressed this, the signal-receiving features of the two electrodes may provide a clue. The ET electrodes record through contact with the vocal cords. When the nerve is stimulated, the vocal cords open and close, and the best contact is reached when the vocal cords close. During the RLN traction injury experiment, the extent of vocal cord closing and action potential decrease gradually. In addition, the position and depth of the ET can easily change[5]. These may all affect the recording response time and sensitivity of ET electrodes. This does not happen with TC electrodes, because they are inserted firmly into the TC and transmit EMG signals through permanent contact with the tissues. Thus, TC electrodes may be more sensitive than ET electrodes because there is no shift or interference, and signals from TC electrodes reflect real-time events more accurately. Another advantage of TC needle electrodes is that significant displacement can be identified easily at the time of surgery[1,6,11,19–21].

This study also evaluated different methods of insertion of TC electrodes, in terms of area, depth and orientation. There was no correlation between EMG amplitude and depth of needle insertion, nor between EMG amplitude and any of the needle orientations tested.

Amplitudes perceived by the TC electrodes in area 4 were significantly higher than those recorded in other TC areas, or by ET electrodes. The EMG result was confirmed by TC specimen analysis. Anatomically, the thyroarytenoid muscle is mainly located in areas 3, 4 and 5 (*Fig. S1*, supporting information). The surgeon should also appreciate that the vocal cord is located approximately halfway down the TC and the lateral and posterior cricothyroid muscles. These muscles also govern movement of the vocal cords, are innervated by the RLN, and are also located in TC areas 4 and 5.

Electrophysiologically, another potential mechanism of transcartilage recording is by sensing muscle activity inside the TC (the voice box). The EMG recording at bilateral TC area 4 was better than that at bilateral areas 1, 2 and 3, because the needle could sense a larger area of muscle activity in the voice box. The EMG amplitude in area 4 was also significantly larger than that of area 3 in the same anatomical transverse plane, and the same was also observed in areas 6 and 2. Thus, anatomical factors may be more influential than electrophysiological factors with regard to signal amplitude. Area 5 is at the edge of the TC, deep in the neck, and the cartilage is close to the surrounding muscle. This makes it difficult to insert the needle reliably in this area. Area 4 in the TC was found to be the optimal area for electrode placement.

The latency values did not differ by type of recording electrode, needle insertion area, needle insertion depth or orientation. This is understandable, as latency is associated only with the length of the nerve conduction pathway[1,22].

The stability of EMG amplitudes from TC electrodes was greater than that from the ET electrodes. This is because the needle tips were inserted firmly into the TC and the receiving portion was visible to the surgeons. Thus, surgeons are able to prevent changes in the position of TC electrodes. These features are very different from those of ET electrodes. ET electrodes are inserted into the trachea and the receiving portion is not visible to the surgeon; only the distal segment of the tube can be fixed around the mouth, but not the recording electrodes. Thus, shifts in the position of ET electrodes can easily occur[3–5,17].

There are limitations to this study, and more experimental and clinical studies are required before translating these findings into clinical practice. Although the method seems logical for conventional bilateral surgery, it may be difficult to expose the bilateral thyroid area in order to insert the needle electrodes in some unilateral operations with a small incision, or in endoscopic procedures. There are also some issues regarding complications associated with needle electrodes. Needle recording electrodes inserted into the muscle around the larynx raise the possibility of trauma, including laryngeal haematoma and vocal cord laceration, and also infection, cuff deflation, need for reintubation, retained fractured needle segment, and accidental needle dislodgement during surgery[1]. In this experimental study, the mean thickness of TC areas 4 and 5 exceeded 3 mm, and the EMG amplitude did not correlate with needle insertion depth or orientation. Perichondral insertion to a depth of less than 3 mm into the avascular area 4 may be a safe and effective method for placement of the needle electrode.

IONM has been an effective auxiliary tool in the surgical management of thyroid disease, not only in the USA and Europe, but its use is also increasing in Asia, with institutions beginning to perform more monitored thyroidectomies[9,23,24]. New technologies in surgery can, however, lead to increases in healthcare costs, because they are more expensive than previous treatments[25,26]. TC electrodes have an obvious advantage over ET electrodes in terms of cost. The present findings could pave the wave for a non-invasive IONM recording electrode to be designed in the near future, which could be applied quickly and easily and be able to transmit an optimal EMG signal.

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Supporting information

Additional supporting information can be found online in the Supporting Information section at the end of the article.