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Comparative Effectiveness of Recurrent Laryngeal Nerve Monitoring Techniques in Pediatric Surgery

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Objectives/Hypothesis: The recurrent laryngeal nerve (RLN) is at risk during pediatric cervical, thoracic, and cardiac surgery. We aim to determine the feasibility and effectiveness of RLN monitoring techniques in all pediatric patients.

Study Design: Retrospective case series.

Methods: Retrospective review of patients/procedures with RLN(s) at risk and RLN monitoring at Boston Children's Hospital July 2019–October 2020. Primary outcomes: pre/postoperative vocal fold mobility by awake flexible fiberoptic laryngoscopy (FFL).

Results: One hundred one patients (median [interquartile range, IQR] age 14.6 months [4.6–49.7 months], weight 10 kg [5.2–16.2 kg]) underwent 122 procedures with RLN(s) at risk. RLN monitoring attempted 111 cases, successful 96 (84%). Surgical indications: esophageal atresia/tracheoesophageal fistula, and tracheobronchomalacia. Sixty-two (56%) procedures in reoperative field. Median follow-up 112 days (IQR 41–230). Pre/postoperative FFL performed 84 procedures (69%), 19 new postoperative RLN injuries (16%), median age 12 months, reoperative fields 11 (18%). Prass probes: 34 cases (28 successful, 82%), 6 injuries (18%), age 12.2 (5.8–23.6) months. Dragonfly electrodes: 45 cases (37 successful, 82%), 8 injuries (18%), age 7.5 (3.8–19) months. Nerve integrity monitoring (NIM) integrated electrode endotracheal tube: 33 cases (33 successful, 100%), 5 injuries (15%), age 90 (58.8–136.7) months. Automatic periodic stimulation (APS): 16 cases, 13 successful (81%), four injuries (25%), age 7.2 (5.3–20.6) months. NIM RLN monitoring is significantly more successful than Prass, Dragonfly (95%CI −0.3 to 0.02, $P = .02$; and 95%CI 0.05–0.31, $P = .008$). Rates of injury are not different between types of RLN monitoring ($P = .94$), with APS use ($P = .47$), or with monitoring success (95%CI −0.36 to 0.09, $P = .28$).

Conclusions: RLN monitoring is feasible in pediatric patients of all ages. Although NIM type RLN monitoring success is superior, all forms offer similar rates of nerve protection.

Key Words: Recurrent laryngeal nerve, recurrent laryngeal nerve monitoring, recurrent laryngeal nerve injury, esophageal atresia, tracheobronchomalacia, tracheoesophageal fistula, pediatric thoracic surgery, pediatric neck surgery.

Level of Evidence: 3

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INTRODUCTION

The recurrent laryngeal nerves (RLNs) are branches of the vagus nerves that carry motor, sensory, and parasympathetic fibers to the larynx. The RLNs are at risk during cervical, thoracic, and cardiac surgery as the nerves often course through the operative field. Risk of RLN injury during surgery for esophageal atresia (EA), tracheoesophageal fistula (TEF), and tracheobronchomalacia (TBM) has been documented in the literature. In these cases, the frequency of RLN injury ranges from 11% to 50% with variation by approach, patient anatomy, concurrent cardiac procedures, and degree and timing of RLN injury ascertainment.[1–7] Identifying and protecting the RLN is particularly challenging in the surgery of neonates, with increased anatomic complexity, and in reoperative cases.[7]

RLN injury with subsequent vocal fold immobility (VFI) and loss of laryngeal sensation may result in significant morbidity for pediatric patients, including respiratory distress (typically inspiratory stridor), feeding difficulties including laryngeal penetration and aspiration, recurrent respiratory infections, and voice changes.[1,8] The clinical course for patients with iatrogenic RLN injury can vary greatly depending on the duration of dysfunction, whether the immobility is unilateral or bilateral, and the presence of associated comorbidities (laryngomalacia, laryngeal cleft, and tracheomalacia) that can be exacerbated by a RLN injury. Spontaneous recovery after iatrogenic injury may occur in approximately 25% to 46% and has been documented as late as 4 years after the insult.[8,9] When mobility does not return, additional interventions may be necessary, ranging from diet modification to injection medialization, thyroplasty, tracheotomy, and gastrostomy tube placement.[8] Iatrogenic bilateral VFI is a serious complication, which

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may require placement of tracheotomy for airway obstruction and/or aspiration. More recent conservative measures have resulted in a tracheotomy rate of 57% to 69% of these patients.[10] Persistent dysphonia can have both social and academic impact on pediatric patients.[11]

Intraoperative nerve monitoring (IONM) provides immediate feedback to the surgeon on RLN location and function during surgery.[1,12] In adult patients, IONM demonstrates a 99% negative predictive value and 75% positive predictive value of intraoperative nerve signaling loss and postoperative vocal fold paralysis.[13] Routine utilization of IONM in pediatric surgery has faced challenges including adaptation of the equipment to pediatric patients, the need to alter the anesthetic management of the patient during surgery, presence of equipment in the surgical field, and training of the surgeons on the use of IONM and nerve preservation strategies. There are several currently available options for IONM during pediatric cervical and thoracic surgery, including integrated, or adhesive surface electrodes on endotracheal tubes (such as Medtonic NIM TriVantage electromyograph [EMG] Tube, Medtronic, Jacksonville, Florida and Neurovision single or double-channel Dragonfly Stick on EMG Electrode, Neurovision Medical Products, Ventura, California, respectively) and endolaryngeal or translaryngeal electrodes (such as Prass-paired electrodes). Automatic periodic stimulation (APS) (Medtronic, Jacksonville, Florida) is a real-time RLN monitoring that may be used in conjunction with one of above-mentioned IONM options. Each technique has advantages and disadvantages. At our institution, we utilize all these different methods of RLN monitoring in pediatric patients of all ages during cervical, thoracic, and cardiovascular surgery. The objective of this study is to determine the feasibility and effectiveness of RLN monitoring techniques in pediatric patients of all ages and sizes.

MATERIALS AND METHODS

We retrospectively reviewed all patients who underwent cervical, thoracic, and cardiac procedures that placed one or both RLNs at risk and employed RLN monitoring techniques at Boston Children's Hospital from July 2019 to October 2020 under an approved institutional review board protocol (IRB-P0004344). Exclusion criteria included patients who did not undergo RLN monitoring and patients for whom the chart information was incomplete.

A review of patient records was conducted and data including patient age and weight at the time of surgery, surgical indications, previous surgeries, preoperative vocal fold mobility, surgical procedures performed, total number of operations, type of monitoring, success of monitoring, postoperative vocal fold mobility, and length of follow-up were collected. Main outcomes measured included pre- and postoperative vocal fold mobility as assessed by awake flexible fiberoptic laryngoscopy (FFL). All pre- and postoperative flexible fiberoptic vocal fold mobility assessments were performed by pediatric otolaryngologists. Monitoring was considered successful when stimulating the RLN intraoperatively with a nerve stimulator probe resulted in appropriate feedback or signal from the monitoring system.

RESULTS

One hundred one patients (median [interquartile range, IQR] age 14.6 months [4.6–49.7 months] and weight 10 kg [5.2–16.2 kg], 65 males, 36 females) underwent 122 procedures with either one or both RLN at risk. RLN monitoring was attempted in 111 cases and was successful in 96 cases (84%). The primary surgical indications included EA, TEF, and TBM. Surgical approaches included cervical, midline sternotomy, lateral thoracotomy, and open laparotomy; cases were performed open, thoracoscopically, and/or robotically. Airway surgeries included anterior and/or posterior cervical tracheopexy, anterior and/or posterior thoracic tracheopexy, mainstem bronchopexies (left, right, bilateral), tracheal resection, descending posterior aortopexy, anterior aortopexy, and resection of tracheal diverticulum. Esophageal surgeries were primary and secondary EA repair, primary and secondary TEF repairs, spit fistula creations, esophagectomies, stricturoplasty, stricture resection, Foker procedures, leak and perforation repair, and many others depending on the individual patient's anatomy. Each patient underwent multiple concurrent procedures during a single trip to the operating room. Sixty-two (56%) procedures were in a reoperative field. There were 22 preexisting individual RLN injuries (22%). Median length of follow-up was 112 days (IQR 41–230 days). Pre- and postoperative FFL was performed for 84/122 procedures (69%) during which we identified 19 new RLN injuries (16%), 10 right RLN, eight left RLN, and one bilateral. The median age of patients with a new RLN injury was 12 months compared to 15.8 months in patients without RLN injury (95%CI −24.4 to 13.4, $P = .56$). There were 11 new injuries in reoperative surgery (18%) compared to eight new injuries in naïve surgical fields (16%) (95%CI −0.08 to 0.17, $P = .61$). There were 15 new injuries in cases with successful monitoring (14%) compared to four new injuries in unsuccessful monitoring cases (27%) (95%CI −0.36 to 0.09, $P = .28$).

Comparison of the different monitoring techniques can be found in Table I. The RLNs were monitored with endolaryngeal Prass probes in 34 cases (28 successful,

TABLE I.
Comparison of RLN Monitoring Techniques by Monitoring Success, Patient Age, and Rate of RLN Injury.

Type of Monitoring	Cases, n	Monitoring Successful, n (%)	Age, mo (IQR)	Injuries, n (%)
Endolaryngeal Prass probes	34	28 (81)	12.2 (5.8–23.6)	6 (18)
Dragonfly adhesive electrodes	45	37 (82)	7.5 (3.8–19)	8 (18)
NIM-integrated electrodes	33	33 (100)	90 (58.8–136.7)	5 (15)
APS	16	13 (81)	7.2 (5.3–20.6)	4 (25)

APS = automatic periodic stimulation; IQR = interquartile range; RLN = recurrent laryngeal nerve.

82%), with six injuries (18%), median (IQR) age 12.2 (5.8–23.6) months. Dragonfly adhesive electrodes on endotracheal tubes (ETT) were used in 45 cases (37 successful, 82%), with 8 injuries (18%), median (IQR) age 7.5 (3.8–19) months. NIM integrated electrode ETT were used in 33 cases (33 successful, 100%), with five injuries (15%), median (IQR) age 90 (58.8–136.7) months. APS was used in 16 cases concurrently with NIM, Dragonfly, and Prass monitoring, 13 successful (81%), with four injuries (25%), median (IQR) age 7.2 (5.3–20.6). NIM type RLN monitoring was significantly more successful than Prass and Dragonfly (95%CI −0.3 to −0.02, $P = .02$; and 95%CI 0.05 to 0.31, $P = .008$, respectively) although rates of nerve injury were not significantly different between the different types of RLN monitoring ($P = .94$) or with APS use ($P = .47$).

DISCUSSION

Our data demonstrate that IONM is both feasible and effective in children of all ages undergoing pediatric surgery during which one or both RLNs are at risk. We utilized three available RLN monitoring techniques, as well as APS, and although NIM was more successful at monitoring the RLN, they all appear equally effective at protecting the nerve. Ultimately, consideration should be given to the advantages and disadvantages of each technique case-by-case during surgical planning. One must also take into account the patient's size, subglottic space, and surgical exposure. Being familiar with all techniques will allow one to adapt and provide a custom approach to each child.[1] Consistent with literature to date, our series underscores the risk to the RLN during pediatric cervical, thoracic, and cardiac surgeries, with 16% experiencing a new RLN injury postoperatively. The RLN is a relatively small nerve which has a long course that often passes through a significant portion of the operative field in surgery for EA, TEF, TBM, and cardiac vascular surgery, placing them at high risk of injury. The RLN anatomy may also be abnormal in the setting of EA/TEF, aberrant vasculature, and cardiac anomalies, making it more challenging to anticipate the location of the nerve. We had hypothesized that the left RLN might be injured more frequently than the right RLN given its longer intra-thoracic course, but our injury laterality rates were fairly even.

The nerve can be particularly challenging to identify in neonates and reoperative fields. The median age of patients with a new RLN injury was 12 months compared to 15.8 months in patients without injury. It is important to note that nearly 50% of the patients were undergoing procedures in a reoperative field, which makes identification of the RLN more challenging due to scar and postsurgical anatomic changes. In our series, reoperative cases had a greater rate of nerve injury than surgically naïve patients (18% vs. 16%).

The NIM-integrated EMG electrode ETT (Fig. 1) resulted in the highest rate of successful RLN monitoring in our series. In every case it was used, the surgical team was able to stimulate the monitored RLN using a nerve stimulator probe and elicit appropriate feedback from the monitoring system. This affords the surgeon the confidence that the monitoring system would alert them to inadvertent stimulation of the RLN. We attribute the high rate of successful nerve monitoring with NIM tubes to ease of use, increased surgeon familiarity, and because the integrated electrodes are less likely to slip and be displaced intraoperatively. Despite this, the rate of RLN injury with NIM monitoring was comparable to other methods studied (15%). Advantages of NIM-integrated electrodes and the Medtronic monitoring system include wide availability and decreased risk of electrode slippage as the electrodes are integrated into the ETT. The primary disadvantage of the NIM ETTs in pediatric surgery is their size: currently, the smallest endotracheal tube available is cuffed with a 5.0 mm inner diameter (ID), 6.5 mm outer diameter, appropriate for a child aged 4 years and older. In our series, the median age for

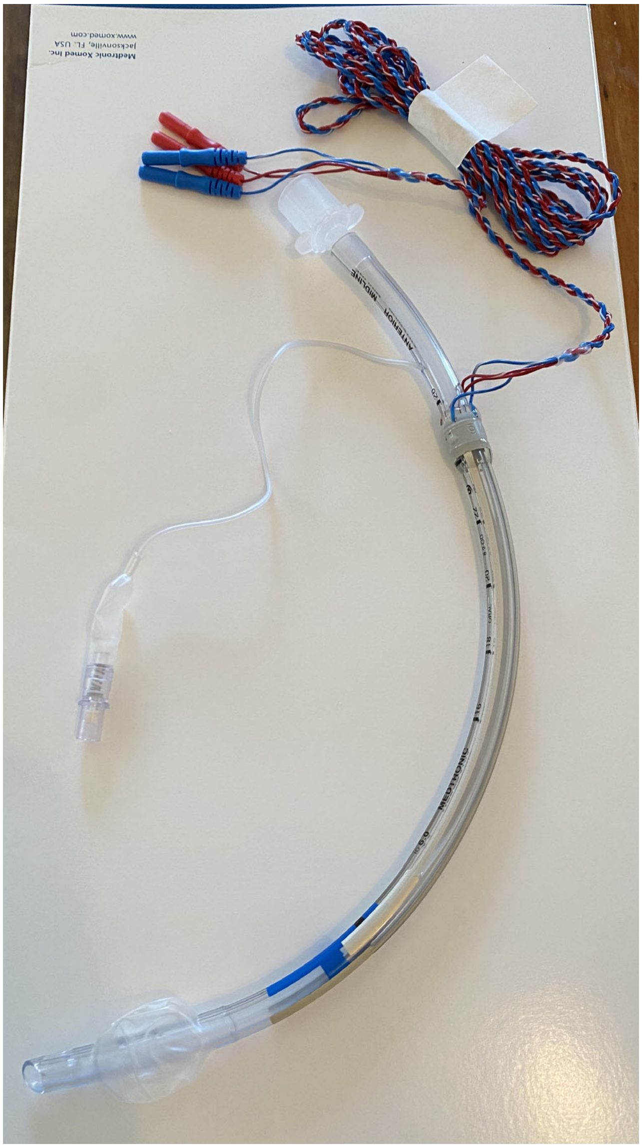

Fig. 1. Medtronic NIM Trivantage EMG-integrated electrode endotracheal tube size 6.0 mm ID. EMG, electromyograph; ID, inner diameter

NIM-integrated EMG electrode ETT use was 90 months or 7.5 years. Additional challenges to this method of monitoring include improper placement of the EMG electrodes between the true vocal folds with poor detection of vocal fold stimulation, providing the surgeon with a false negative response and unexpected postoperative nerve injury. The ETT may also move with patient positioning even after adequate placement is confirmed during laryngoscopy. The system's alert is slightly delayed and not "real time," thus, if the nerve is accidentally transected, the surgeon may only notice after the injury when the audible and visual warning is elicited from the NIM system. Noisy signal feedback and false positive nerve stimulation may also inhibit accurate monitoring.

The Dragonfly adhesive electrode ETT (Fig. 2) was used to successfully monitor the RLN in 82% of cases, which was equal to the endolaryngeal Prass electrodes, with a comparable nerve injury rate (18%) to all other monitoring methods studied. A significant advantage of the Dragonfly adhesive electrode ETT is their use in younger children. In our series, Dragonfly ETT were used in younger children than the NIM-integrated electrodes, median age of 7.5 months versus 90 months. Dragonfly integrated electrodes are available in single-channel and double-channel adhesive electrodes. Single-channel adhesive electrodes are available commercially for ETT as small as 2.0 mm ID but do not allow for monitoring of each nerve individually. Thus, if one nerve is injured intraoperatively, the surgeon may not be alerted by the system because the contralateral nerve is functioning. Double-channel electrodes allow for monitoring of each nerve individually. Unfortunately, integrated and adhesive double-channel electrodes (monitor each RLN separately) are only available in ETT appropriate for children aged 4 years or older. Successful modification of the Dragonfly double-channel adhesive electrode to accommodate an ETT as small as 3.0 mm ID (term neonate) and to allow for individual RLN monitoring has been previously published and this modification was used in this series.[14] Disadvantages of the Neurovision Dragonfly adhesive electrode ETTs are similar to those for the NIM ETT with the addition of potential adhesive electrode slippage in the setting of long cases and airway secretions.

Endolaryngeal Prass electrodes were used with a high rate of successful monitoring (82%) comparable to the Dragonfly ETT and a comparable nerve injury rate (18%) to all other monitoring methods studied. The Prass-paired electrodes are compatible with the NIM monitoring system and may be used in children of any age although they may be bulky in small neonates. Direct laryngoscopy is used to expose the larynx, and the double-pronged electrode is placed just lateral to the vocal cords into the vocalis (Fig. 3). The leads are secured to the patient externally. Alternately,

Fig. 2. Neurovision Dragonfly sticks on electrodes wrapped around the distal end of standard endotracheal tubes.

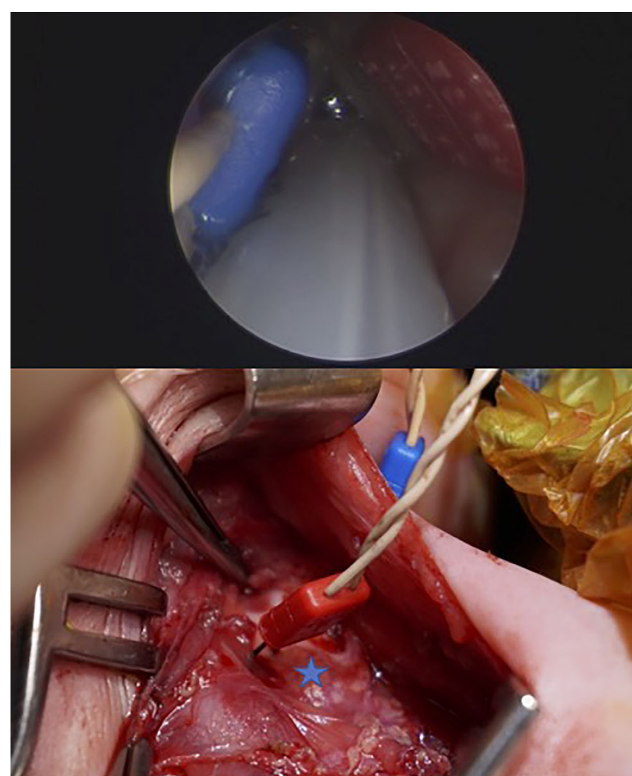

Fig. 3. Top: Direct laryngoscopy view of Prass-paired electrodes (blue for left and red for right) placed just lateral to the vocal folds. Bottom: Prass-paired electrodes placed translaryngeal into the vocalis muscle. The red electrode (right) is placed through an open incision, the blue electrode (left) is placed through the skin because the cervical incision did not extend to the left neck. Star: thyroid cartilage.

the Prass electrodes can be placed through the thyroid cartilage into the area of vocalis muscle if the thyroid cartilage is in the operative field (translaryngeal application, Fig. 3). Advantages of the Prass-paired electrode over other endolaryngeal electrodes (e.g., hookwire) include its sturdiness. Disadvantages include the time and technical skill required to insert the electrodes endoscopically. If the patient has a difficult airway to expose on direct laryngoscopy, this limits the ability to place the electrodes. The electrodes can be dislodged accidentally during the procedure. As these electrodes are needles placed lateral to the patient's vocal folds, there is theoretical risk of laryngeal trauma, edema, hematoma, and bleeding.

The Medtronic APS technique provides continuous real-time stimulation and monitoring of the vagus nerve, and thus the RLN. It is used in conjunction with conventional laryngeal RLN monitoring methods, including NIM, Dragonfly, and Prass electrodes. APS differs from conventional IONM techniques in that APS provides continual feedback on nerve function, whereas there is only intermittent stimulation by a stimulating probe when using other methods.[15] APS can alert the surgeon in real time when EMG latency and amplitude are affected by intraoperative events. To our knowledge, this is the first report of successful RLN monitoring with the APS system in children. APS monitoring is feasible in even young children, with the youngest patient in this series aged 5.3 months. Despite its many advantages, the greatest limitation of the use of APS is that it requires a cervical approach to the carotid sheath to place the electrode on the vagus nerve (Fig. 4). If a cervical approach is not planned for the primary procedure, this technique is of low utility or would necessitate a separate neck dissection. The APS also has the potential to elicit undesirable vagal stimulation. Furthermore, the smallest size of the APS probe is 2 mm, which can be too big for some neonatal vagal nerves, and hence not provide good contact with the nerve. As laryngeal electrode placement is required for use with APS, the advantages and disadvantages inherent to that technique would also apply.

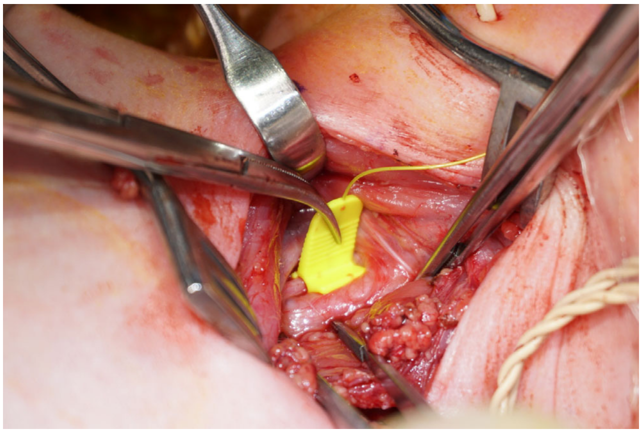

Fig. 4. APS electrode placed around the vagus nerve during a left neck dissection. Sternocleidomastoid is retracted laterally to expose carotid sheath. APS, Automatic periodic stimulation.

There appeared to be a higher rate of nerve injury in cases without successful nerve monitoring than in those that did have successful monitoring with appropriate feedback or signal from the monitoring system (27% vs. 14%) although it did not achieve statistical significance. Preliminarily, this suggests that use of the nerve monitor may be protective although it is underpowered. Unfortunately, it was not always clear in the operative reports when the nerve monitoring signal was lost- it may have been at the start of the case, or it may have been later in the procedure when monitoring had been used for a significant portion of the surgery. An area of active investigation is comparison of RLN injury rates in pediatric thoracic, cardiac, and cervical cases with and without RLN monitoring.

Although this represents the largest series describing the efficacy of RLN monitoring in pediatric surgery, limitations of this study include the relatively small cohort and its retrospective nature. Given the unique, complex anatomy, and specifically tailored surgical approaches required for these patients, we are unable to identify which indications or procedures place the patient at greater risk of RLN injury. We have also not yet implemented IONM in every surgery at our institution where a RLN is at risk, so there may be unconscious selection bias to the cases presented here. We have included every case since we began using IONM at our institution and a learning curve to successful IONM may be present in these data. The COVID-19 epidemic significantly reduced the number of FFL that were performed in the months of March to May 2020, thus limiting our data collection during that time. Not all of these IONM methods may be available for every surgeon at every institution. Nerve injury identified in the immediate postoperative period is not always permanent[7] and long-term follow-up of recovery of vocal fold mobility in this population is ongoing. Finally, there is also no control group in this series to compare the rate of RLN injury in cases with and without IONM, and this is an area of ongoing study.

CONCLUSION

The RLN is at significant risk during pediatric cervical, thoracic, and cardiac surgery, especially in younger patients and reoperative fields. RLN monitoring is feasible in pediatric patients of all ages and sizes using commercially available technology. Although NIM type RLN monitoring success is superior, all forms appear to offer similar rates of nerve protection. APS can be used in pediatric patients to provide real-time feedback to surgeons when cervical approach is utilized. There is an inherent learning curve for the operative team both with installing and setting up the IONM, the anesthetic management, as well as surgical RLN identification and preservation.

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