

ORIGINAL ARTICLE

A preliminary evaluation of the surgery to reconstruct thoracic breathing in patients with high cervical spinal cord injury

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Study design: A prospective study.

Objectives: To evaluate the effect of the surgery to reconstruct thoracic breathing in patients with high cervical spinal cord injury (CSCI).

Setting: China Rehabilitation Research Center, Beijing, China.

Methods: The posterior ribs (from the fifth to the eighth) were suspended on the inferior angle of the scapula on each side using titanium cables, as well as muscles and myofascial tissue in the subscapular area. After the surgery, the patients were trained for synchronous contraction of the trapezius and diaphragm muscles, and electromyography (EMG) was performed to evaluate the synchronization. The clinical symptoms and pulmonary function were assessed within 1 week before surgery and at 2, 12 and 24 postoperative weeks.

Results: Six patients with complete high CSCI received rib suspension surgery 84 ± 26.7 days after spinal cord injury. Before the surgery, all of the patients presented with weakened cough, retention of respiratory secretions and dyspnea, while these symptoms alleviated postoperatively. The vital capacity (VC) was enhanced to be 1680 ± 282 ml at 2 weeks after the surgery, compared with 1085 ± 92 ml ($P = 0.013$). The EMG showed a synchronous muscle electrical activity between the trapezius muscles and diaphragm during deep breaths.

Conclusion: The rib suspension surgery partially restored the thoracic breathing of the patients with high CSCI, thereby improving VC, cough and expectoration.

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INTRODUCTION

Partial or complete diaphragmatic paralysis frequently occurs in cervical spinal cord injury (CSCI) and causes severe respiratory dysfunctions, such as weakened cough, retention of respiratory secretions, dyspnea and even respiratory arrest. It has been reported that, in patients with CSCI in the acute hospitalization phase, nearly 84% had respiratory complications, 20% underwent tracheostomy and mechanical ventilation and 4–5% required lifetime ventilatory support.¹

The trapezius muscles, dominated by spinal accessory nerves, can have an important role in reconstructing the respiratory function of patients with CSCI.² The trapezius muscles (mainly innervated by the first and second levels of spinal cord, C1–2) ends at the spine of the scapula and has auxiliary inspiration function with the coordination of the muscles that attach the scapula to the rib cage. However, due to extensive muscle paralysis caused by CSCI, the scapula will slide up along the rib cage when the trapezius muscle contracts. Hence, the auxiliary inspiration effect is basically abolished in patients with CSCI. Theoretically, the trapezius muscle strength is well preserved in patients below C2 level and can be surgically transferred to the rib

cage through the scapula to recover the lost thoracic breathing, thus to improve respiratory function and to enhance cough and expectoration.

We developed an innovative surgical technique using the trapezius muscles that we call rib suspension surgery (or thoracic breathing reconstruction). The surgery is mainly applicable for high CSCI, which accounts for 18.5% of the population with spinal cord injury.³ Here, we report the preliminary evaluation of the effect of the surgery.

MATERIALS AND METHODS

Studied population

Medical history, including age, sex, cause of disease, concomitant injuries, complications, concomitant diseases and so on, was collected. Patients, 18–60 years old, C2–4 complete spinal cord injury with the remnants of diaphragmatic function, trapezius muscle strength of grade 4 or 5 and dyspnea were eligible for the surgery. Patients were excluded with the following conditions: cerebral trauma combined with disturbance of consciousness, multiple rib fractures, scapular fractures, severe osteoporosis and ankylosing spondylitis.

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Surgery

General anesthesia was induced via tracheal intubation. The patient was placed in the prone position with 30–45° shoulder abduction. Around the inferior angle of the scapula, an arc-shaped incision was made between the inferior angle line of the scapula and the posterior axillary line. The lowest point of the incision was within the sixth and seventh ribs (Figure 1a). The inferior angle of the scapula and ribs 5–8 were revealed. The extrapleural ribs 6 and 7 (or 7 and 8) were separated, with a segment approximately 1 cm long. Around the separated ribs, a titanium cable (1.3 mm in diameter; Zimmer, Cable Grip System, Warsaw, IN, USA) was punctured to bind up ribs 6 and 7 (or 7 and 8), with a total of four ribs suspended in the inferior angles of both sides (Figure 1b).

After the suspension with the cable, the teres major and fascia stripped from the inferior angle of the scapula were folded and stitched on the intercostal muscles and fascia adjacent to the inferior angle of the scapula. The exposed serratus anterior was also sutured to the intercostal muscles and fascia within the fifth and eighth ribs (Figure 1c).

Breathing training

Every acute patient with high CSCI was routinely given 30 min of breathing training once a day by a therapist, including strengthening the power and endurance of the diaphragm, sternocleidomastoid and trapezius muscle, giving auxiliary abdominal aid and giving auxiliary thoracic aid. The intensive training usually began at 2 weeks postinjury. After the rib suspension surgery, the intensive breathing training was suspended for 2 weeks to avoid the dehiscence of the surgical incision. But the patient was allowed to cough and given auxiliary expectoration if necessary. After 1 week, synchronous breathing exercises were started, which is, in deep inspirations, the trapezius muscle is kept in synchronous and isometric contraction. The training duration was 2 or 3 min for 4–6 times every day. After 2 weeks, the synchronous and intensive breathing training was maintained until they were discharged from hospital.

Clinical evaluation

All clinical assessments were conducted within 1 week before surgery and at 2, 12 and 24 postoperative weeks, unless otherwise specified.

Neurological assessment

The spinal cord impairment and level was evaluated using ASIA (American Spinal Injury Association) Impairment Scale.⁴

Respiratory assessment

Cough and expectoration. There were three levels of cough and expectoration: were weakness (cough was weakened, voluntary expectoration can be performed), aid (cough was significantly weakened, expectoration can be performed with auxiliary abdominal aid, such as ‘Quad Cough’ from a health professional or caregiver), and disability (the patient underwent tracheotomy and required clearance of sputum with a suction catheter). The changes with time in cough and expectoration were evaluated when the patient was in supine position.

Phonation ability. Patients were asked to subjectively rate their phonation ability postoperatively. To compare with that before operation, phonation ability at postoperation was categorized as worse, no change, improved or satisfactory. For patients with an endotracheal tube, the assessment is performed with the tracheostomy tube temporarily blocked.

Ventilation dependence. The three levels of dependence on ventilation were continuous ventilation (24 h a day), intermittent ventilation (at least over an hour a day) and no ventilator support.

Oxygen dependence. The three levels of dependence on oxygen inhalation were continuous (24 h a day), intermittent (at least over an hour a day) and no oxygen inhalation.

Diaphragmatic activity. Diaphragmatic impairment was classified into bilateral complete paralysis, bilateral weakened activities, unilateral weakened activity and unilateral complete paralysis. To compare with the diaphragmatic activities before operation, the change of diaphragmatic motion at 2 weeks postoperation were measured by chest fluoroscopy² and categorized as weakened, no change or increased.

Pulmonary function test. The test was performed twice with the patient in the supine position (Sorinnes-B-5503, Medisoft S.A, de Ciney, Belgium). No bronchodilators were used pretesting, no additional abdominal binder was used, the vital capacity (VC) recordings were done via the mouth and the optimal measurement with the maximum VC was used. For the patients with an endotracheal tube, the leakage from the tracheal incision should be prevented during the test. When an endotracheal tube with a cuff was used, the cuff was deflated or the tube was first replaced by a metal endotracheal tube (diameter, 11 mm).

Arterial blood gas analysis. The conventional arterial blood gas analysis was performed before operation and at 2 weeks postoperation. In patients with oxygen inhalation, the blood samples were drawn after withdrawing oxygen inhalation for 15 min.

Electromyographic examination

Electromyography (EMG) was performed to evaluate the trapezius muscles and diaphragm at 3 months after operation (Dantec Keypoint 4G, Natus Medical Incorporated, San Carlos, CA, USA). With the patient sitting in a wheelchair, for the trapezius EMG, the surface recording electrode was placed on the middle of the upper edge of the trapezius muscle and the reference electrode on the posterior midline at T2 level; for the diaphragmatic EMG, the surface recording electrode was placed in the eighth intercostal space on the anterior axillary line and the reference electrode in the sternum xiphoid zone. The synchronous recording was conducted in the pattern with quiet breathing and with deep breathing.

Surgery-related complications

The limitation of shoulder joint and scapula activity, healing of the surgical incision, rupture of the suspended cables and fractures of suspended ribs and scapulas were recorded. The passive shoulder joint activities, including the flexion–extension, abduction–adduction and intorsion–extorsion ranges, were

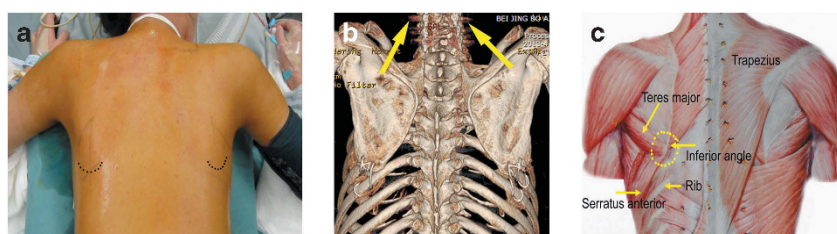


Figure 1 Surgical anatomy and surgery. (a) Surgical incision. (b) The inferior angle of the scapula and the ribs were bound with the titanium cables. The yellow arrows indicate the resultant force on the scapula, which resulted from the contraction of the trapezius muscle. (c) Muscle distribution in the subscapular area.

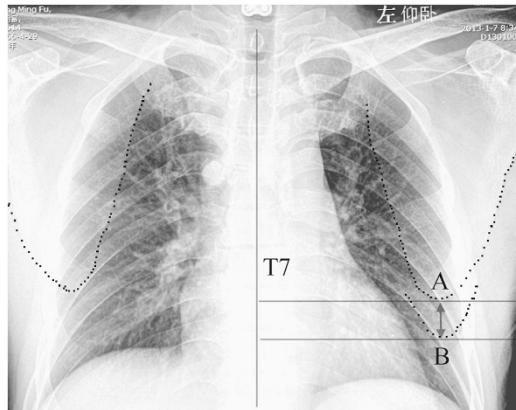


Figure 2 Measurement of the scapula activity. A, The lowest position of the inferior angle while the trapezius muscles were at maximum contraction; B, the lowest position of the inferior angle while the trapezius muscles were relaxed; AB, the sphere of activity of the scapula.

measured. The anteroposterior chest radiographs were obtained in the position with shoulder 30–45° abduction when the bilateral trapezius muscles were relaxed and contracted as far as possible. The vertical displacement of the inferior angle of the scapula relative to the spinal midline (Figure 2) was used to approximately describe the activity of the scapula.

Data analysis

Results were reported as mean ± s.d., unless otherwise specified. Repeated measures analysis of variance was used to determine the significance of VC and tidal volume (TV) changes over time. A paired *t*-test was used for the analyses of shoulder joint activity, inferior angle activity and arterial blood gas. *P* < 0.05 was considered statistically significant.

Ethical approval

The study was approved by the ethics committee of the China Rehabilitation Research Center (approval No. 2013LL-004).

RESULTS

A total of six patients received thoracic breathing reconstruction after providing written informed consent through their entrusted agents. All the patients had severe high CSCI (ASIA, Grade A, motor score, 0.2 ± 0.4 points). The mean age of the patients was 41.7 ± 16.2 years. At 11.8 ± 10.3 days after injury, the patients underwent internal fixation of the cervical spines. At 6 ± 5.8 days after injury, the patients underwent tracheotomy and ventilator support because of inadequate secretion clearance and/or dyspnea. The application duration of the ventilator was 45.3 ± 25.9 days. The application duration of endotracheal intubation before the surgery was 81.6 ± 29.8 days and 25.4 ± 7.2 days after the surgery. The rib suspension surgery at the bilateral inferior angles of the scapula was performed 84 ± 26.7 days after injury.

Neurological changes

The results of the neurological assessment within 1 week before rib suspension surgery were compared with those at 2 weeks post-operatively. No recovery in sensory or motor functions was observed in the patients. After 3 months, the functions of the deltoid and biceps muscles in one patient were partially recovered (the deltoid muscles restored to grade 3 bilaterally, the right biceps to grade 4 and the left to grade 3). After 6 months, all the six patients still had complete spinal cord injuries. The detail of the neurological changes is shown in Table 1.

Table 1 Neurological changes

No	OT	Neurological level	Motor scores	Sensory scores	Impairment scale	Trapezius strength	Deltoid strength	Biceps strength	Diaphragm activity	
Postinjury										
		Pre-O	2 weeks	12 weeks	Pre-O	2 weeks	12 weeks	Pre-O	2 weeks	12 weeks
1	78 days	C2	C2	28	A	5/5	0/0	3/1	Weak	Increased
2	49 days	C4	C4	26	A	4/4	0/0	0/0	Weak	Increased
3	69 days	C3	C3	26	A	5/5	0/0	0/0	Weak	Increased
4	52 days	C4	C4	32	A	5/5	1/0	3/1	Weak	Increased
5	120 days	C3	C3	25	A	5/5	0/0	0/0	Weak	Increased
6	110 days	C2	C2	18	A	4/4	0/0	0/0	Weak	Increased

Abbreviations: OT, operation time, refers to the time of the rib suspension surgery; Pre-O, preoperation, that is, before the rib suspension surgery; Recording of muscle strength: right/left.

Table 2 Respiratory changes

No.	Sex	Age	Causes	Expectoration			Phonation			Ventilator support			Oxygen inhalation		
				Pre-O	2 weeks	12 weeks	Pre-O	2 weeks	12 weeks	Pre-O	2 weeks	12 weeks	Pre-O	2 weeks	12 weeks
1	F	26	Traffic	Disability	Aid	Weakness	Weak	Improved	Satisfied	No	No	No	Intermittent	No	No
2	M	46	Fall	Disability	Aid	Weakness	Weak	Improved	Satisfied	No	No	No	Continuous	No	No
3	M	18	Traffic	Disability	Aid	Weakness	Weak	Improved	Satisfied	No	No	No	Continuous	No	No
4	M	52	Fall	Disability	Aid	Weakness	Weak	Improved	Satisfied	No	No	No	Intermittent	No	No
5	M	60	Traffic	Disability	Aid	Weakness	Weak	Improved	Satisfied	Intermittent	No	No	Intermittent	No	No
6	F	48	Traffic	Disability	Aid	Weakness	Weak	Improved	Satisfied	Intermittent	No	No	Intermittent	No	No

Abbreviations: F, female; M, male; Pre-O, preoperation, that is, before the rib suspension surgery.

Respiratory changes

Before the surgery, the patients presented with loss of thoracic breathing, significantly weakened abdominal breathing and weakened cough. Due to secretion clearance disability, all the patients required suctioning via endotracheal intubation. Chest fluoroscopy revealed significantly reduced diaphragmatic activity. During deep inspiration, the displacement of the diaphragmatic vertex was within one intercostal space. One day after surgery, patients reported easier breathing and improved cough and expectoration. Fluoroscopy examination within 2–3 weeks after surgery showed increased range of diaphragmatic activity (1.2 ± 0.9 cm). Endotracheal intubations were all successfully removed within 4 weeks after surgery, and the patients were able to participate in activities with the aid of wheelchair. The details are shown in Table 2.

The preoperative VC was 1085 ± 92 ml, and the VC at 2 postoperative weeks was 1680 ± 282 ml, which was increased by 55% ($P = 0.013$). The VC at 12 weeks postoperative was further increased by 130 ml compared with the VC at 2 weeks postoperative. The changes in TV at 2 and 12 weeks postoperative weeks were not significantly increased compared with the preoperative TV (Figure 3).

The PaO₂ (partial pressure of oxygen) was 80.5 ± 14.1 mm Hg preoperatively and 92.0 ± 4.2 mm Hg at 2 weeks postoperative, respectively. The SpO₂ (oxygen saturation) were $97 \pm 2\%$ and $99 \pm 1\%$, respectively. The PaCO₂ (partial pressure of carbon dioxide) were 35.9 ± 1.4 mm Hg and 38 ± 3.5 mm Hg, respectively. The changes in PaO₂ were significant ($P = 0.04$).

Electromyographic results

Under the deep inspiration mode, a synchronous activity was visible between the trapezius and diaphragmatic EMG (Figure 4). Compared with the diaphragmatic EMG activity, the trapezius EMG activity was a cluster of sparse pulse waves.

Surgery-related complications

The activity of the shoulder joint was slightly restricted after the rib suspension surgery. It mainly affected the abduction activity of the shoulder joint. Compared with that before operation, the passive abduction activity was reduced by $9.7 \pm 7.2^\circ$ at 12 weeks after surgery. The disadvantages of the rib suspension surgery on the activity of the shoulder joint did not discount the motor function of the upper limbs.

The position of the inferior angle of the scapula was higher, mostly between the fifth and sixth ribs, in the patients with CSCI than in the healthy population. The shifting up was caused by the pulling of the functional trapezius muscle. The vertical range of subscapular movement was 3.4 ± 2.2 cm preoperatively and 2.4 ± 1.6 cm at 3 months

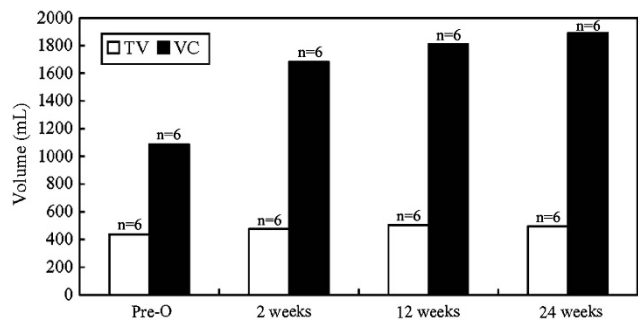


Figure 3 Pulmonary function. The white bar represents the TV; the black bar represents the VC; the mean of the predicted VC is 4227 ml.

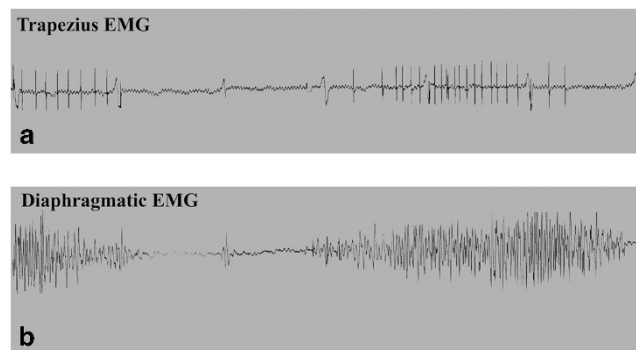


Figure 4 EMG. (a) trapezius EMG and (b) diaphragmatic EMG.

postoperative. The position of the inferior angle was helpful in locating the optimal surgical incision.

Wire breakage occurred on the right side after 3 months in the first case, and the wire was removed 2 weeks later. Intraoperative ascertainment revealed the existence of cutting signs in the bundled places of the ribs and scapula. Pleural rupture occurred in another patient during intraoperative separation of the ribs. One patient had delayed incision healing due to suppression in bed. Within 2 weeks after surgery, two patients complained of pains in the scapular area, which spontaneously disappeared after reducing the intensity of the breathing training.

DISCUSSION

Effects and mechanism

A wide range of muscle paralysis occurs in patients with high CSCI, so that their bodies are in a state of low-energy consumption.

Accordingly, they can adapt to a hypopnea state. Many patients in the chronic phase have only low TV, that is, 200–300 ml (in Asians), but they do not feel uncomfortable. At such TV, patients seem to maintain their basic metabolism. Usually, when the VC reaches 17 ml kg^{-1} , most patients could be off the ventilator support.⁵ However, they could not adapt to a higher metabolic state (for example, fever and increased activities). By the rib suspension surgery, the VC in this group of patients was increased by 55% at 2 weeks postoperative. The significant change in VC was further confirmed in a baseline study of VT and TV with time in CSCI population (see supplemental control group). Because of the improved VC, the corresponding increase in the reserves of lung functions enabled the patients to adapt to higher metabolic levels, reducing their dependence on oxygen inhalation and ventilator. The improved cough and expectoration could also help patients to reduce pulmonary complications.

The significant improvement of VC after surgery may be related to the postoperative breathing training and/or the natural recovery of the injured spinal cord. However, as there was no recovery in the neurological evaluation at 2 weeks after surgery compared with before surgery, the intensive breathing training was suspended 2 weeks after surgery. The prompt improved VC was reasonably associated with the surgery. But, what is the underlying mechanism? The respiratory movements in healthy individuals included thoracic and abdominal breathing. The contraction of inspiratory muscles involved in thoracic breathing could cause increase in the anteroposterior and left–right thoracic diameters; the contraction of the diaphragm muscles involved in abdominal breathing could cause a decline in the diaphragmatic ridge, resulting in an increase in vertical diameter. The synergy of thoracic and abdominal breathing could effectively result in an increase in the thoracic volume during inhalation. During one deep breathing action in healthy individuals, thoracic breathing accounted for approximately 40% contribution and abdominal breathing (diaphragm) accounted for 60%.⁶ In addition, the energy consumption of respiratory motion was primarily related to the inspiratory muscles. A large amount of the energy consumption was stored in the form of elastic potential energy during thoracic and lung expansion and then passively released during exhalation. There were obvious abnormal respiratory patterns in the patients with high CSCI (see Supplementary Video S1), that is, the respiratory power directly decreased, the thoracic wall was invaginated for the negative intrathoracic pressure during the contraction of the diaphragm and, especially, the loss of support from the zone of apposition of the diaphragm to the rib cage (or the decline against the contraction of the diaphragm) could significantly weaken the residual diaphragmatic work efficiency.^{7,8} We analyzed the outcomes of rib suspension surgery and concluded that it might improve respiratory functions based on the following aspects: (1) the trapezius muscle was a powerful auxiliary inspiratory muscle, which could be involved in synchronization with the diaphragm and provide thoracic breathing power; (2) after suspension of ribs 5–8, when a tension force was applied on the lower thoracic wall against the invagination of the wall, more air could have been inhaled; and (3) expanding the lower transverse dimension of the lower rib cage increased diaphragmatic effectiveness (Figure 5).

Surgical design

The trapezius muscle mainly ends at the scapular spine and external one-third of the clavicle. From the anatomical point of view, the strength of the upper trapezius muscle can be transferred to the front of the rib cage through the clavicle or to the back of the cage through

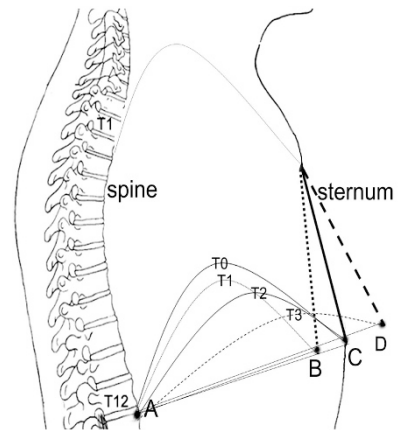


Figure 5 Schematic sagittal section of the thoracic cage. AB, AC and AD show the sagittal diameters of the thoracic cage at the invaginated, normal and expanded states, respectively; T0, T1, T2 and T3 show the top of diaphragm at different states. L_{A-T0-C} is the sagittal length of the diaphragm without contraction. When the diaphragm contracts at the same extent ($L_{A-T1-B} = L_{A-T2-C} = L_{A-T3-D}$) and the thoracic cage is at its invaginated, normal and expanded states, the decreased range of diaphragmatic vertex would be at the invaginated state \prec at normal state \prec at expanded state. This means that at the expanded state more air can be inhaled.

the scapula. We selected the latter route for the following reasons: (1) the rib suspension surgery at the bilateral inferior angles of the scapulae is simple, and there are no important neurovascular structures around the inferior angle; (2) the force in the suspension arm was less than that in the front suspension way, but the suspended fifth to eighth ribs were the initiation region of the front diaphragm and beneficial to expand the caliber under the thorax; and (3) the sternocleidomastoid, which is also innervated by the spinal accessory nerves and starts from the front of the sternum manubrium and sternal end of the clavicle to the mastoid process, can pull the sternum from the front of the rib cage. A collaborative anteroposterior inspiration power is established for thoracic breathing. It must be emphasized that, in our designs, the cables mainly support the temporary transition and have an immediate role after surgery, and the durable and reliable suspension is based on the sutured muscles and fascial structures; hence, the rib suspension using soft tissue is very important.

Complications

The following are five potential complications of the surgery: surgical damage to the intercostal vessels and nerves, fractures of suspended ribs and scapulars, rupture of the suspended cable, bed sore on the scapular area, and limited shoulder mobility. We did not encounter damage to intercostal vessels and nerves; nevertheless, it must be emphasized that the intercostal vessels and nerves should be carefully stripped together with the rib bed to avoid damage or bound up by the cables. In the first case, wire breakage occurred on one side 3 months after surgery, mainly because of the use of ordinary wire bundles with poor strength and fatigue resistance. In the succeeding five surgical cases, we used titanium cables and expanded the suspension range of the muscle fascia, in which the lower serratus anterior muscle and teres major were used to strengthen the suspension of the ribs. Neither the stress cutting of the cable bundle nor the titanium cable breakage occurred again. As the skin in the scapular area is prone to compression, the incision should not be

directly extended to the skin over the scapula, and careful nursing care was necessary to prevent compression of the incision. Shoulder joint activity was a little restricted after the surgery.

CONCLUSIONS

There are of course many limitations of this preliminary study for a new surgery technique. To properly evaluate the early surgical outcome, a study with larger sample and randomized control group should be performed in the future. In addition, long-term effects and complications should also be evaluated. However, the effects of the surgery are partial restoration of thoracic breathing, improvement in VC, reduction in need for tracheostomy for secretion clearance, reduction in need for ventilation support and supplemental oxygen therapy and subjective changes to phonation.

DATA ARCHIVING

There were no data to deposit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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- 1 Onders RP, Elmo M, Khansarinia S, Bowman B, Yee J, Road J *et al*. Complete worldwide operative experience in laparoscopic diaphragm pacing: results and differences in spinal cord injured patients and amyotrophic lateral sclerosis patients. *Surg Endosc* 2009; **23**: 1433–1440.
- 2 Yang ML, Li JJ, Zhang SC, Du LJ, Gao F, Li J *et al*. Functional restoration of the paralyzed diaphragm in high cervical quadriplegia via phrenic nerve neurotization utilizing the functional spinal accessory nerve. *J Neurosurg Spine* 2011; **15**: 190–194.
- 3 DeVivo MJ, Krause JS, Lammertse DP. Recent trends in mortality and causes of death among persons with spinal cord injury. *Arch Phys Med Rehabil* 1999; **80**: 1411–1419.
- 4 Maynard FM Jr., Bracken MB, Creasey G, Ditunno JF Jr., Donovan WH, Ducker TB *et al*. International Standards for Neurological and Functional Classification of Spinal Cord Injury. American Spinal Injury Association. *Spinal Cord* 1997; **35**: 266–274.
- 5 Chiodo AE, Scelza W, Forchheimer M. Predictors of ventilator weaning in individuals with high cervical spinal cord injury. *J Spinal Cord Med* 2008; **31**: 72–77.
- 6 Creasey G, Elefteriades J, DiMarco A, Talonen P, Bijak M, Girsch W *et al*. Electrical stimulation to restore respiration. *J Rehabil Res Dev* 1996; **33**: 123–132.
- 7 Brown R, DiMarco AF, Hoit JD, Garshick E. Respiratory dysfunction and management in spinal cord injury. *Respir Care* 2006; **51**: 853–868; discussion 869–70.
- 8 McCool FD, Pichurko BM, Slutsky AS, Sarkarati M, Rossier A, Brown R. Changes in lung volume and rib cage configuration with abdominal binding in quadriplegia. *J Appl Physiol* 1986; **60**: 1198–1202.

Supplementary Information accompanies this paper on the Spinal Cord website (<http://www.nature.com/sc>)