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STATE-OF-THE-ART

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THORACIC

Sternal elevation techniques during the minimally invasive repair of pectus excavatum

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Key question

Do sternal elevation techniques (SET) during minimally invasive repair of pectus excavatum (MIRPE) improve the safety of the procedure?

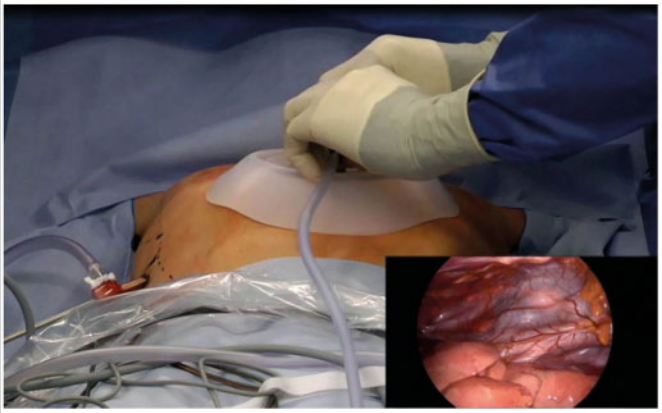
Key finding(s)

Various SET for MIRPE have been described, all resulting in the improved safety of the procedure.

Take-home message

SET during MIRPE should be a routine manoeuvre. The vacuum bell is the ideal measure for this because it is both effective and noninvasive.

Intraoperative use of the vacuum bell



Summary

The aim of the review was to evaluate the routine use of sternal elevation techniques (SETs) during minimally invasive repair of pectus excavatum (MIRPE, the Nuss procedure). We performed a review of the literature between January 1998 and September 2018 with focus on different methods of SET during MIRPE. Reported effects and side effects were evaluated and compared with our own experience concerning the routine use of the vacuum bell for sternal elevation during MIRPE during the last 13 years. SET is more often used in adult patients than in adolescents. SET improves visualization and safety of MIRPE. Advancement of the pectus introducer, retrosternal dissection and placement of the pectus bar are easier. The risk of cardial and/or pericardial lesion is reduced significantly. Different types of retractors, a crane combined with a wire and/or customized hooks are reported to be used as SET. Furthermore, routine use of a subxiphoid incision is reported. However, more technical equipment, and in some SETs additional incisions are necessary. In contrast, no additional skin incision is necessary for the vacuum bell. The routine intraoperative use of the vacuum bell was safe and effective in 131 patients. It facilitates

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the retrosternal dissection and the insertion of the pectus bar like other SETs. Besides a temporary mild hematoma, no relevant side effect was observed. In conclusion, an increasing number of authors report on the routine use of SET during MIRPE to improve safety of the procedure. We recommend the routine intraoperative use of the vacuum bell during MIRPE.

Keywords: Sternal elevation • Vacuum bell • Intraoperative use • Nuss procedure

INTRODUCTION

The minimally invasive repair of pectus excavatum (MIRPE), first described by Nuss in 1998 [1], is well established and represents the worldwide 'gold-standard' for surgical repair of pectus excavatum (PE) in paediatric, adolescent and adult PE patients. However, despite its minimally invasive approach, with the widespread use of the MIRPE procedure, the character and number of complications have increased [2–9]. Moreover, numerous recent studies report on an increasing number of near-fatal complications [9–15]. During MIRPE, the blunt retrosternal dissection required to pass the pectus bar across the mediastinum is a potentially dangerous manoeuvre. Visualization across the mediastinum is compromised in severe defects, and cardiac puncture and aortic injury have been described [15]. Notably, in adult patients, stiffness and rigidity of the chest wall and the corresponding force required to elevate the sternum may hamper retrosternal dissection. The most severe complication is cardiac perforation from the insertion of the introducer and from the positioning of the pectus bar. Intraoperative cardiac perforation remains a rare but potentially lethal risk. The incidence of cardiac perforation is unclear, but numerous case reports demonstrate that it continues to occur [9, 11]. Different modifications to the original method have included the use of thoracoscopic guidance to avoid inadvertent blind injury to the heart and the mammary vessels. The introduction of routine thoracoscopy decreased the rate but failed to eliminate cardiac perforations completely [11, 15, 16]. However, a recent analysis of contemporary practice in 50 ACS NSQIP-paediatric institutions (the American College of Surgeons 2012 National Surgical Quality Improvement Program-Paediatric) revealed that routine thoracoscopy is used in only 84% of the participating centres [6]. An increasing number of authors report on the routine use of the sternal elevation technique (SET) during MIRPE to increase safety and decrease the complication rate of the procedure.

The aim of this review was to study the recent literature focusing on different techniques of SET used during the MIRPE procedure, including our own experience using the vacuum bell for sternal elevation during MIRPE for more than 10 years.

METHODS

Publications describing the use of SET during the MIRPE procedure were identified. Specific terms were: 'sternal elevation', 'minimally invasive repair of pectus excavatum', 'MIRPE' and 'Nuss procedure'. The databases used were: PubMed, Embase, Scopus and MEDLINE, together with the first 10 pages of Google Scholar. The search was restricted to English-language articles and human studies, between January 1998 and September 2018. Appropriate studies that reported the use of intraoperative sternal elevation were included. After removal of duplicates, 23 article abstracts were reviewed. Articles that did not qualify as original research were excluded.

The technique and use of the vacuum bell for conservative treatment of PE and its intraoperative use during MIRPE are described elsewhere [17–20]. Our preliminary experience encouraged us to use the device intraoperatively to facilitate the dissection of the transmediastinal tunnel and the advancement of the pectus introducer [17]. When creating the vacuum, the elevation of the sternum is obvious and persists for a distinct period of time [18]. Therefore, the use of the vacuum bell was also considered to be useful in reducing the risk of injury to the heart and the mammary vessels during the MIRPE procedure. The individual components of the vacuum bell (plastic and silicone) are sterilizable. However, the intraoperative use of the vacuum bell has to be considered as 'Off-label'. In agreement with our hygiene department, we used a gas plasma technique for sterilization of the vacuum bell. Three different sizes of the vacuum bell exist [19, 20]. The diameter is 16 cm of the small model, 19 cm of the medium size and 26 cm of the large model, respectively. The medium size model is available in a supplemental version with a reinforced silicon wall, e.g. for adult patients with a small deep pectus. The appropriate type and model of the device was determined according to the individual patients' chest wall size [19, 20]. Routine intraoperative use of the vacuum bell during MIRPE is being performed since 2005.

RESULTS

The review comprised the current literature within the last 20 years. After removal of duplicates, 23 article abstracts were reviewed. The majority of identified studies report on different external applied devices to elevate the sternum, in combination with additional incisions (see Table 1). Focusing on older adolescent and adult PE patients, Yoon *et al.* [21] lifted the depressed sternum by means of a crane device using the Kent retractor. The sternum is elevated by pulling the wires, which are sutured to the sternum, rotating the bar. St Peter *et al.* [22] introduced a subxiphoid incision to allow finger guidance to protect the mediastinum. All operations included 2 lateral incisions, 1 subxiphoid incision and 2 lateral stabilizers. With the subxiphoid incision, the need for thoracoscopy was obviated. Park *et al.* [23] introduced the employment of the crane technique using wire stitches to elevate the depressed sternum in adults, teenagers or patients with severe depressions to avoid heart injury.

Takagi *et al.* [24] developed a handheld sternal elevator that is inserted through an anterior-lateral incision in the thoracic wall under thoracoscopic vision. Their handheld sternal elevator will be held by an assistant standing at the patient's left side creating sufficient space between the sternum and the heart. Tedde *et al.* [25] described a technique using 2 Langenbeck retractors inserted through the same incisions as the pectus bar to pull the chest wall up, whereas the heart is moved down by its own weight.

Johnson *et al.*'s [26] technique includes a 3-cm subxiphoid incision and a novel sternal lift system that elevates the sternum. Bond and Nagaraj [27] modified the standard Nuss procedure

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Table 1: Sternal Elevation Techniques (SETs) listed from the literature

Author	Year	Number of patients	Extra device	Extra skin incision
Yoon *et al.* [21]	2010	44	Kent retractor	No (wire/puncture)
St Peter *et al.* [22]	2010	307	Subxiphoid incision	Yes
Park *et al.* [23]	2010	1170	Crane	No (wire)
Takagi *et al.* [24]	2012	61	Sternal elevator	No
Tedde *et al.* [25]	2012	25	Langenbeck retractor	No
Haecker *et al.* [20]	2012	50	Vacuum bell	No
Johnson *et al.* [26]	2013	NA	Subxiphoid incision	Yes
Bond *et al.* [33]	2013	73	Subxiphoid incision	Yes
Jaroszewski *et al.* [28]	2014	63	Rultract® retractor	No (clamp)
Rygl *et al.* [29]	2014	180	Wolkmann bone hook	No (puncture)
Jeong and Lee [30]	2014	61	Crane	No (wire)
Takahashi *et al.* [32]	2015	1	Kent retractor	No (wire/puncture)
Park *et al.* [31]	2015	1816	Crane	No (wire)
Haecker *et al.* [20]	2016	131	Vacuum bell	No
Gould *et al.* [34]	2017	554	Subxiphoid incision	Yes

using again a subxiphoid incision with central fixation to maximize safe bar passage and minimize bar displacement.

A modified retractor system used for adult patients was described by Jaroszewski *et al.* [28] in 2014. A bone clamp is placed into the sternum and a table-mounted retractor is used to elevate the sternum. The Rultract® retractor with extension arm is attached to the left side of the table, at an approximate level with the clavicle. The cable is then attached to the clamp, and the sternum is elevated. Rygl *et al.* [29] use a Wolkmann bone hook, which is percutaneously inserted to the distal sternum to create sufficient space between the sternum and the heart. Jeong and Lee [30] again confirmed the advantage of intraoperatively using the crane technique for sternal elevation. Park *et al.* [31] continued using the crane in a larger patients group, 5 years after his first publication.

Takahashi *et al.* [32] reported on the usefulness of Kent retractor and lifting hook during MIRPE, and Bond *et al.* [33] confirmed their experience using the subxiphoid incision in a recently published paper. Another study including a larger series of PE patients confirmed the addition of a subxiphoid incision to the MIRPE as a reasonable measure for safe passage of the bar across the mediastinum to avoid cardiac injury [34].

Based on our good and comprehensive experience using the vacuum bell for conservative treatment of PE, we started in 2005 with a pilot study concerning the intraoperative use of the vacuum bell during MIRPE [17]. This application was first described by Schier *et al.* [18]. Three different sizes of the vacuum bell and a specially shaped model for women allow to find the appropriate type and model of the device according to the individual patients' chest wall size.

A total of 131 patients aged from 9 to 28 years (average 16.02 years, median 16 years; 104 men and 27 women) who were operated on for PE underwent the use of the vacuum bell intraoperatively. A subset of this series was previously published [17]. The preoperative Haller index was between 3.25 and 12.4 (average 6.05). The duration of surgery averaged 48 min (range 40–92 min). 1 pectus bar with 1 lateral stabilizer was used in 120 patients; in 11 patients 2 pectus bars were introduced. The vacuum bell was applied for retrosternal dissection and advancement of the pectus introducer including placement and flipping of the pectus bar. Thoracoscopy confirmed clear elevation of the sternum (Figs 1–3). Neither cardiac and/or pericardiac lesions nor lesions of the mammary vessels were noted intraoperatively by using right-sided thoracoscopy [17]. Additionally, no midline skin incision was necessary to elevate it with the sternum. In our operating room, routine intraoperative application of the vacuum bell is an essential part of the standardized MIRPE since more than 10 years [19, 20]. A recently published paper, confirmed the immediate effect of sternal elevation even after the first application [35].

In summary, within the last 10 years, an increasing number of authors report on the routine use of sternal SET during MIRPE. Of course, there were no randomized studies comparing MIPRE with and without SET. Owing to the low rate of cardiac and mammarian artery injuries using these techniques, it is unjustifiable to draw up plans for randomized or case–control studies. The most commonly used techniques and devices include extrathoracic procedures like the crane technique with a wire or a retractor, different types of special hooks, an additional subxiphoid incision and the vacuum bell as a sternal lifter (Table 1). The safety of MIRPE was clearly improved as there was no near-fatal and/or fatal incident reported anymore during surgical repair of PE. None of the patients reported in the different studies sustained a cardiac injury.

DISCUSSION

One of the most important steps of MIRPE is the advancement of the pectus introducer to dissect a retrosternal tunnel for the implant. Visualization and dissection across the mediastinum in patients with severe PE may be impaired by the inwardly displaced sternum. Meticulous preparation is mandatory to prevent greater complications such as a cardiac lesion or major bleeding. As reported by Hebra *et al.* [9], the prevalence and type of these life-threatening complications are unknown and under-reported. Furthermore, they noticed that life-threatening lesions are not only related to the MIRPE but may also occur during bar removal [9, 16]. Of course, operating on paediatric and young adolescents including PE patients with mild deformity, SET is not needed in every MIRPE. Furthermore, using 2 pectus bars for PE correction, the first introducer might be introduced higher than the deepest

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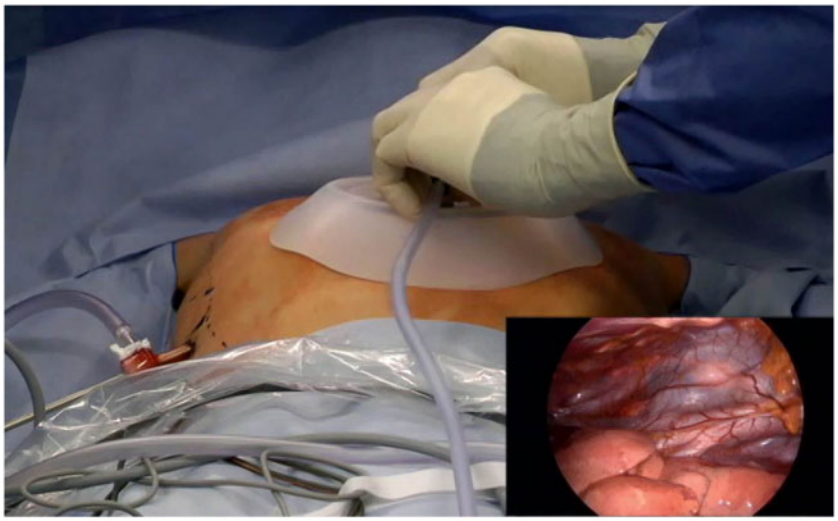

Figure 1: Intraoperative use of the vacuum bell.

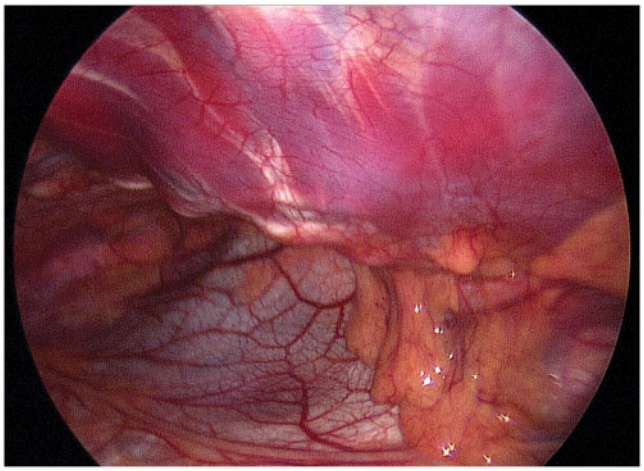

Figure 2: Intraoperative use of the vacuum bell, see right-sided thoracoscopic view before application of the vacuum bell.

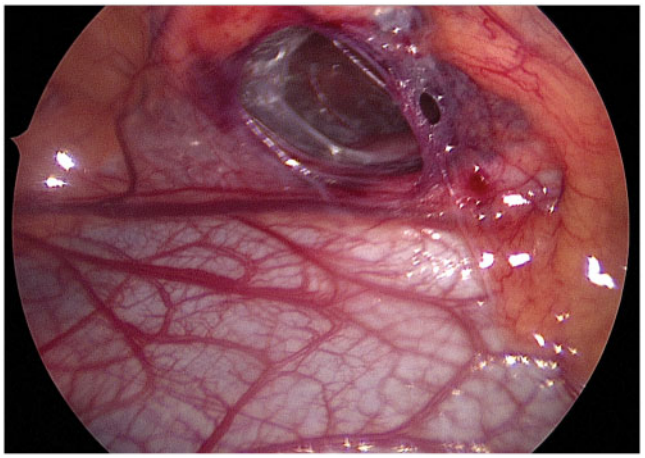

Figure 3: Intraoperative use of the vacuum bell, see the clear elevation of the sternum with direct view to the contralateral side.

point, which might be helpful to create a safe tunnel for the second introducer.

The aim of our review was to study the recent literature focusing on different SET's used during MIRPE to prevent life-threatening complications. The technique of forced sternal elevation during surgical repair is in particular used in adolescent and adult MIRPE cases. Expanding the retrosternal space has been recommended by many authors to minimize pericardial trauma and eliminate cardiac perforation [24–26]. SET may facilitate safe dissection and bar passage and reduce the risk of intercostal muscle stripping. As we notice less chest wall flexibility in adult patients, the bars require more force to rotate and it may result in intercostal muscle stripping. Sternal elevation may prevent muscle stripping.

Objective parameters such as maximum elevation or a redefined (elevated) Haller index including the measurement of forces required to enable a safe turn of the bar are missing in the reviewed literature, and randomized studies comparing MIRPE with and without SET. Papers reporting on standardized SET like the Crane technique or the Rultract retractor technique mention the effectiveness, but no objective data concerning measured values. The use of handheld devices like the handheld sternal elevator described by Takagi *et al.* [24], the Wolkmann bone hook [29] or Langenbeck retractors [25] are dependent on the personal strong forces, and obviously cannot be assessed. Weber *et al.* [36] reported in 2006 for the first time on systematic tension measurements to assess the effect of individual steps in the mobilization of the sternum. However, only tension measurement was performed, and surgical repair was performed as open repair. Based on our own experience with the intraoperative use of the vacuum bell, neither intensity nor duration of SET is the most important aspect, but the effect which enables visualization and safe retrosternal dissection and safe placement of the pectus bar. We do not use a standardized number of pumps to elevate the sternum. We connect the vacuum bell to the aspiration device to elevate the sternum until the skin touches the glass of the vacuum bell. Of course, the majority of PE patients in whom we applied the intraoperative use of the vacuum bell during MIRPE, were adolescents and young adults. However, our oldest PE patient was 38 years old. There is no doubt that in older patients with a rigid chest wall and/or in redo-procedures, the crane technique might be more effective and useful for SET than the intraoperative vacuum bell application.

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Figure 4: Pectus excavatum patient before minimally invasive repair of pectus excavatum.

Figure 5: Pectus excavatum patient after minimally invasive repair of pectus excavatum. See the mild haematoma after intraoperative use of the vacuum bell.

As summarized in Table 1, a couple of recent published studies report on the routine use of a subxiphoid midline incision, either for direct blunt dissection to allow finger guidance to protect the mediastinum, or to insert a Kent retractor or another modified hook [21, 22, 24, 26, 27, 29, 34]. These authors acknowledge that an anterior scar is undesirable, especially in a cosmetic procedure, but they have found that these small incisions with little to no skin stretching heal very well and that patient satisfaction is high. They are convinced that the method of subxiphoid incision with central fixation as a modification of MIRPE has proved to be effective in avoiding the immediate complications of pneumothorax, haemothorax and cardiac perforation, which is confirmed by their results. However, no additional skin incision is appreciated more than a small incision by patients and it eliminates the risk of visible scar formation.

Different other techniques avoid the midline incision (Table 1). The crane technique used by Park and Jeong needs only a small puncture to pass the wire, which will elevate the sternum [23, 30, 31]. As an alternative, Tedde *et al.* [25] report on using a Langenbeck retractor to elevate the sternum. They start with the entrance in the left hemithorax, use the retractor to lift the sternum and expand the retrosternal space, whereas the heart is moved down by its own weight. With the routine use of a short bar, the same skin incision may be used.

The results of our pilot study [17] and the following routine practice have confirmed that the intraoperative use of the vacuum bell during MIRPE is safe, effective and facilitates the introduction of the pectus bar. The most important side effect is a haematoma (Figs 4 and 5), followed by mild emphysema. However, both phenomena are temporary and usually disappear spontaneously before the patient leaves the hospital. In contrast to other SETs, no additional midline skin incision or puncture is necessary, the technique is scarless. Therefore, we recommend the routine intraoperative use of the vacuum bell for MIRPE, which is successful even in patients older than 25 years of age.

Besides safety, cost as an additional aspect has to be considered. Handheld devices like the Wolkmann bone hook or Langenbeck retractors represent standard components of technical equipment in many instrument sets. Using gas sterilization of the device, the vacuum bell is reusable. The price for the device is dependent on different aspects (taxes, shipping, etc.), but in most countries, it is <$1000.00. Technical devices like the Rultract retractor might be on order up to $10 000.00. Of course, all these devices are reusable.

Reviewing the current literature, of course, there was no randomized study comparing safety and outcome concerning MIRPE with SET to MIRPE without SET. However, articles and studies reporting on near-fatal complications were all published before 2011 [10–15]. In our review, we could not find any additional scientific paper reporting on that topic afterwards. There is no doubt that the aspect 'learning curve' has to be kept in mind as a relevant factor. However, SET must also be considered as a relevant aspect to improve the safety of MIRPE.

SET used during MIRPE should aim to improve the quality and safety aspects of the procedure, without any additional visible scar formation. The severity of PE, anterior chest wall flexibility and the patient's age represent important aspects, which may have an influence on the quality and safety of the procedure. We developed a prototype of an electronic measurement device, which enables an objective measurement of the chest wall flexibility [37]. Dependent on the above-mentioned aspects, we recommend using SET as a regular feature during MIRPE.

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CONCLUSION

With the widespread use of MIRPE as 'gold standard' for surgical repair of PE, character and number of complications have increased, and there was an increasing number of near-fatal complications. In the recent literature, an increasing number of authors report on the routine use of SET during MIRPE to improve the safety of the procedure. The most commonly used SET includes the crane technique with a wire or a retractor, different types of special hooks, an additional subxiphoid incision and the vacuum bell as a sternal lifter. The safety of MIRPE has improved clearly as there was no near-fatal and/or fatal incident reported anymore when a SET was applied intraoperatively. In our opinion, SET during MIRPE should be a routine manoeuvre. As the vacuum bell is the least invasive of all the available techniques but no less effective, we recommend its intraoperative application as an essential part of the standardized MIRPE.

Ethical approval: This article does not contain any studies with human participants or animals performed by any of the authors.

Conflict of interest: none declared.

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