Actual technical improvements, future aspects

13

13.1 Thoracic wall deformities: 3-D scanning and computerized remodeling

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13.1.1 Background

The morphological estimation of complex anatomic body regions and of congenital or acquired defects is of great importance for an individualized surgical planning, the operative quality management and for long-term postoperative outcome control [11]. Especially congenital thoracic wall deformities frequently show substantial anterior thoracic wall affections, but only few and often deficient analyzing methods exist to objectively assess the complex three-dimensional (3-D) contour anomalies [19]. In particular, women show associated malformations of the breast soft tissue, which aggravates the 3-D evaluation of the female breast region.

In the last decades different evaluation methods have been presented to classify the severity of an anatomical distortion to enable a more objective quantification of an anterior chest wall depression [3]. Direct linear body surface measurements or radiologic distance measurements (chest X-ray, computed tomography (CT), nuclear magnetic resonance imaging (MRI)) provide specific anthropometric indices to quantify chest wall deformities and to compare the surgically induced contour changes [1, 5, 9, 10]. The generated indices only measure the present body deformity punctiform and along one body axis, they are difficult to standardize and show examiner-dependant measurement inaccuracies. Sometimes even invasive examinations are needed and thus inadequately assess the defect geometry [11].

Conventional documentation and assessment of body surface changes using two-dimensional (2-D) photography also neglect spatial dimensions of the chest wall deformity and because of perspective distortion, lack of metric and 3-D information are not suitable and limited by empiric and subjective examiner interpretation [12]. Modern imaging procedures such as CT and MRI enable reconstruction of the complete thorax with all anatomical structures and also the body surface in three dimensions to provide a more vivid visualization and interpretation of the entire complexity of thoracic wall deformities. Highly disadvantageous herein is the patient acquisition in supine or prone position with resulting soft tissue deformation of the whole breast region, time and cost intensive acquisition and the invasive character of these techniques which disallows a routine application for clinical follow-up examinations at close intervals [8, 18].

This lack of criteria oriented clinical assessment methods raises the necessity for supplement existing techniques with additional evaluation methods to guarantee fast, non-invasive, routine clinical follow-up examinations at close intervals and objective, patient specific 3-D assessment and quantification of the body geometry.

New optical measurement systems for the 3-D body surface assessment fulfill the above named relevant requirements and different clinical applications in the field of plastic, reconstructive and aesthetic breast surgery have been demonstrated [16, 17]. One particular advantage of 3-D surface imaging is the non-invasive patient acquisition which provides a risk-free, non-contact, non-deformable, high-resolution 3-D virtual colored model creation of different and specific body regions. 3-D surface imaging enable precise and accurate pre- and especially postoperative 3-D quantification of shape, volume, surface changes, symmetry, projection, swelling tendency, contour and deformation, close intervals postoperative follow-up examinations and therefore optimizes specific steps in the preoperative surgical planning [7]. Digitalized 3-D datasets allow a well-structured patient documentation and computer-aided analysis and evaluation without the necessity of the patients being physically present. The possibility to work with the stored 3-D data in absence of the patients avoids time consuming patient measurements and enables the surgeon to work with different data versions for different clinical questions in different software solutions and to access, revise and overwork the data at any time, in particular even during surgery [14, 16–18].

Optical systems are based on the measurement principle of triangulation and consist of a transmitter unit (light source) which projects a point upon the measured object and a receiver unit (camera) which detects the reflected

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light. The geometric configuration and the measured angle between the transmitter and the receiver allow the calculation of the correct object point in space and the resulting surface geometry [2]. The measured surface is captured as an accumulation of different single points (point cloud). Every point is defined and computed on the basis of the respective x-, y-, and z-coordinates and provides mathematic precise visualization of the whole body surface [16, 17]. A wide range of optical systems for 3-D surface geometry acquisition exist and are based on different physical principles (stereo(-photo)grammetry, Moiré topographie, pattern/structured light, linear laser scanner, etc.). All optical surface imaging systems have in common that they detect the body surface in a short time without any deformable body contact to create a virtual digitalized 3-D model for later computer-aided analysis. In preliminary studies different body surface imaging systems were tested regarding their potential medical application and found the 3-D linear laser scanner most suitable for clinical applications [4].

By means of different patients with pectus excavatum deformities the vantages and existing limitations of current 3-D visualization techniques regarding objective 3-D quantification, computer-aided surgical planning and the development potential in the field of surgical correction of thoracic wall deformities are presented in the following.

13.1.2 3-D quantification of the body surface geometry

A common challenge in plastic and reconstructive surgery is the correction of congenital or acquired deformities. Precise detection and quantification would provide more security to surgeons during the intervention and would enable an objective quality assurance and thus would ease communication with the patient as well. The body surface geometry is quantifiable using 3-D surface imaging systems. The pre- and postoperative assessment of the breast and thorax region can be accomplished sufficiently precise and accurate using a 3-D linear laser scanner according to a standardized scanning protocol and can be presented as a virtual 3-D model for further computer-aided evaluation with appropriate software [16, 17].

On the one hand the accuracy of the existing scanning systems depends on the capturing speed; on the other hand accuracy depends on the capability to assess larger body regions in one or more steps. Current scanning systems vary enormously in fulfilling these requirements. To capture the whole anatomical region of interest it is often necessary to accomplish multiple surface scans from different angles to capture complex body regions. The capturing process for one single shot takes 1–2 s. More problematic is the creation of a closed 360° 3-D model. Especially congenital thoracic wall deformities are often associated with vertebral column deviation and a 360° scan is helpful to evaluate the deformation in total. To achieve a 360° view, multiple single shot scans must be performed either by changing the patient position according to the fixed scanner or by turning the scanner around the patient when using one single scanner. More complex scanning systems with multiple combined scanning modules are expansive but allow capturing a 360° view model with one single shot. Depending on the scanning system the whole capturing process takes from seconds until several minutes.

The 3-D quantification of the body region in a Cartesian coordinate system allows the creation of a virtual 3-D surface computer model using different algorithms and software. This virtual 3-D model offers several advantages over conventional 2-D photography: beside color information, spatial computation of individual points is possible on the basis of the respective x-, y-, and z-coordinates and virtual rotations of the 3-D model in all three dimensions. Precise and accurate pre- and postoperative volume, surface, distance and symmetry measurements on the virtual 3-D model in absence of the patient are feasible. Multiple visualization possibilities and clearly well-structured documentation of the 3-D shape differences allow a meticulous analysis of the anatomical region of interest. After interactive labeling of specific anatomic breast landmarks it is possible to automate some of the analyzing procedures and to release an automatically generated analysis report.

Several important software analysis functions for the clinical application are demonstrated in Fig. 1.

In contrast to conventional 2-D photography, linear measurements can be performed directly on the body surface using virtual 3-D models and clinical questions regarding breast projection, ptosis, circumference, etc. can be documented and visualized very precisely (Fig. 1a). Even surface anthropometric measurements described in the literature to provide severity indices of the deformity can be performed on a virtual 360° surface model (Fig. 1f). But these anthropometric surface measurements deliver only limited information regarding the complex 3-D deformity. The correct deformity degree regarding breast volume and breast surface deficits (Fig. 1b and c) can be quantified [8, 16, 17]. Further it is possible to compare the whole chest wall region

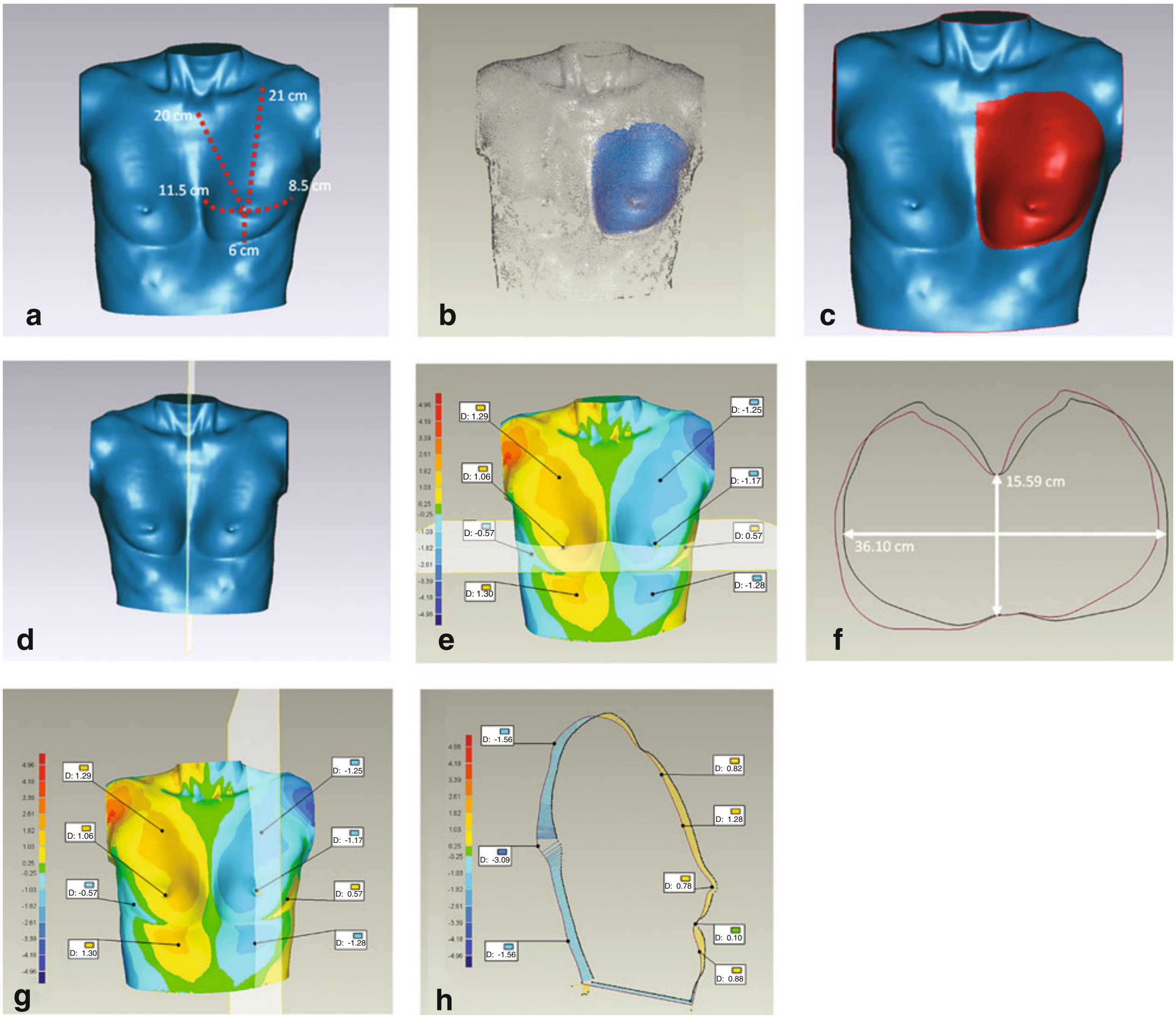

Fig. 1. Different 3-D quantification methods of the thoracic wall: **a** linear on surface measurements; **b** volume measurements; **c** surface measurements; **d** placing symmetric mirror plane; **e** and **g** color-coded quantification of thoracic wall asymmetry by superimposed mirrored 3-D model on the non-mirrored 3-D model and 2-D deviation slice placements; **f** horizontal slice with 2-D deviation of the two models and anthropomorphic thoracic wall measurement at nipple-areola-complex height; **h** sagittal slice between the left and the right thoracic wall with color-coded 2-D deviation at nipple-areola-complex height. All measurements in cm

surface by mirroring an anatomic region of interest (Fig. 1d) for an evaluation of the symmetry of the thoracic wall. By mirroring the 3-D model at the height of the sternum and by superimposing the mirrored model onto the non-mirrored model, precise color-coded quantification of existing or remaining asymmetries of the whole body surface are possible (Fig. 1e and g). Additionally, by placing different slices through the virtual 3-D model (Fig. 1f and h), asymmetries of the contra lateral breast region are visualizable [7, 14]. The visualization of 3-D and 2-D deviations, volume and surface differences etc. deliver important data for an improved preoperative planning of the surgically induced shape transformation [14]. The possibility to compare complex 3-D geometries also permits to superimpose pre- and postoperative 3-D models of a patient and to objectively quantify and evaluate the postoperative results [7]. 3-D surface imaging enables a routine follow-up examination at close intervals and is perfectly suitable for postoperative long time analysis regarding postoperative swelling and soft tissue shape changes over time by superimposing 3-D surface scans accomplished at different examination dates postoperatively. The summary of all these analyzing software functions in an automatically generated report allows quantification of the body surface to optimize surgical procedures as well as an objective quality assurance of the postoperative result and long-term postoperative follow-up studies.

13.1.3 Computer-aided surgical planning

Among others "computer-aided surgery" is aiming at supporting the surgeon during the preoperative planning process and even during the surgery. Through this perspective the influence of existing possibilities and limitations of 3-D imaging and preoperative analysis of the virtual 3-D models concerning the surgical planning process are demonstrated. Most patients undergoing

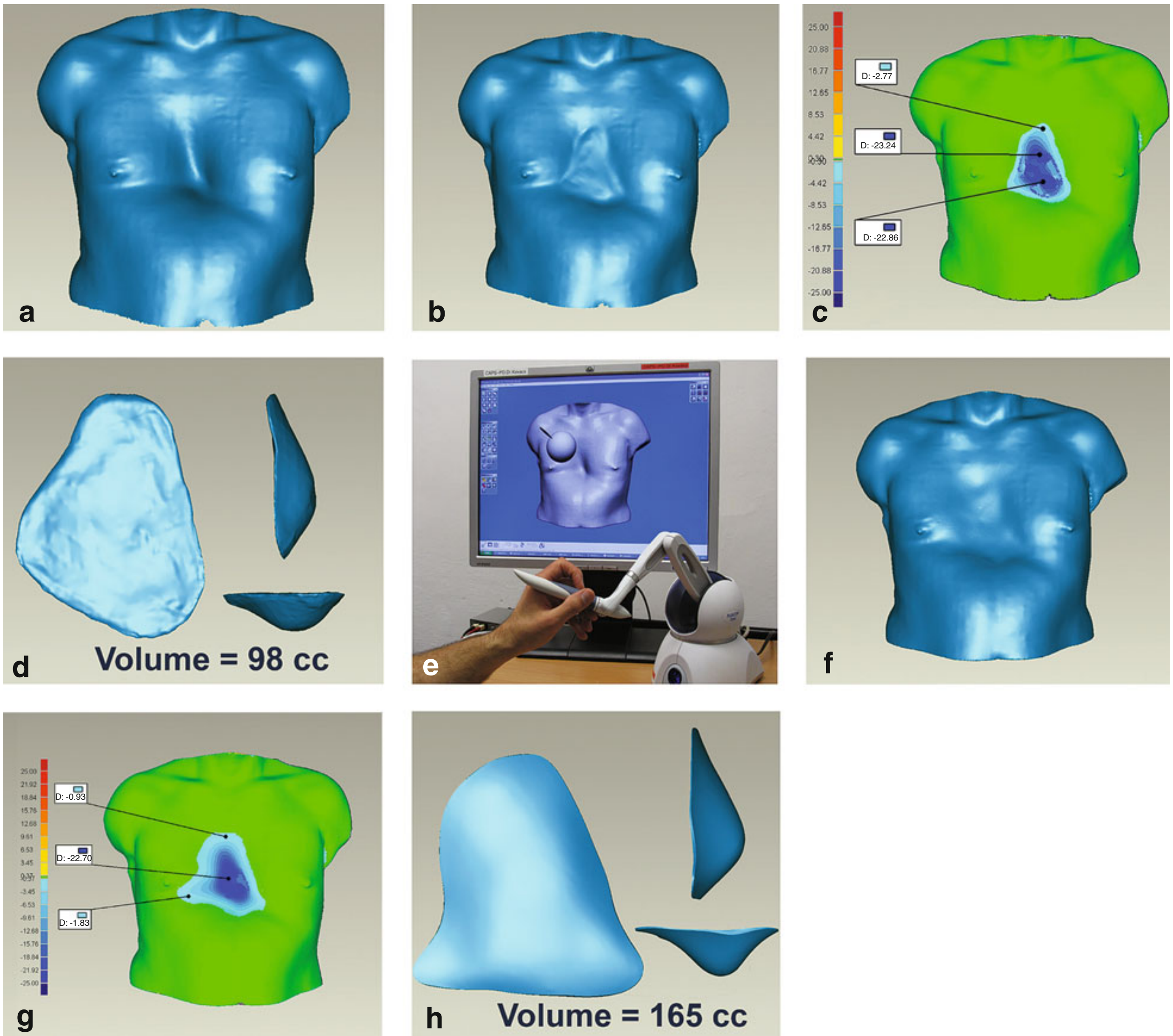

Fig. 2. Computer-aided planning of an silicone implant for chest wall deformity correction: **a** patients preoperative 3-D surface scan; **b** 3-D surface scan with attached conventionally planned silicone implant; **c** 3-D comparison of preoperative 3-D scan and 3-D scan with attached implant; **d** 3-D scan of the conventionally planned silicone implant; **e** force-feedback system for intuitive 3-D haptic interaction with the virtual 3-D model; **f** haptic deformed virtual 3-D model; **g** 3-D comparison of preoperative 3-D scan and haptic deformed 3-D model; **h** computer-aided custom-made silicone implant design by subtracting pre OP scan from deformed 3-D model. All measurements in mm

surgery strongly desire to anticipate the postoperative outcome prior to surgery. Specific software application systems which allow direct interaction of the examiner with the virtual 3-D model enable the surgeon an intuitive virtual 3-D modeling. In analogy to 2-D photography morphing systems it is possible to interactively modify the virtual 3-D model according to the patients and surgeons perception. By means of intuitive modeling of the virtual 3-D model the desired final shape can be displayed. In contrast to conventional 2-D photography not only a visual impression is presented but also concrete comparable measurements for the preoperative planning can be derived from such a 3-D intuitive modeling (Fig. 2).

The degree of thoracic wall deformities, especially of pectus excavatum, is extremely variable and according to their severity requests different reconstruction methods. Severe and symptomatic deformities are corrected with chest wall remodeling, removing affected costal cartilages with sternal repositioning and more mild and asymptomatic deformities can be reconstructed satisfactorily with subcutaneous custom-made silicone implants.

Using the example of a male patient (age: 37 years, height: 194 cm, weight: 100 kg, pectus severity index (PSI): 1.9) with asymptomatic pectus excavatum deformity (Fig. 3), the computer-aided surgical planning of silicone implant contour reconstruction is compared with the conventional planning method using the moulage technique (Fig. 2).

The implant is designed from a moulage taken of the chest wall deformity with the patient in the supine position. The moulage designed implant was 3-D assessed and a virtual 3-D model (volume = 98 cc) of the

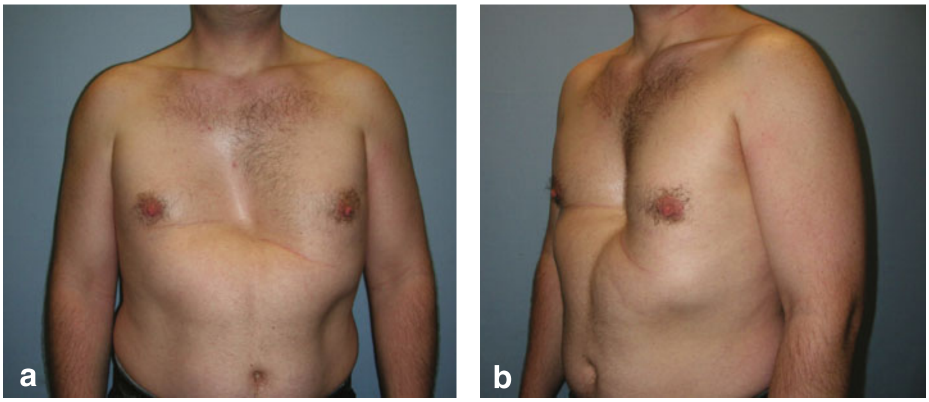

Fig. 3. Preoperative 2-D photography of an asymptomatic 37-year-old male patient undergoing pectus excavatum correction with custom silicone implant: **a** frontal and **b** oblique view of lower third sternal contour deformity

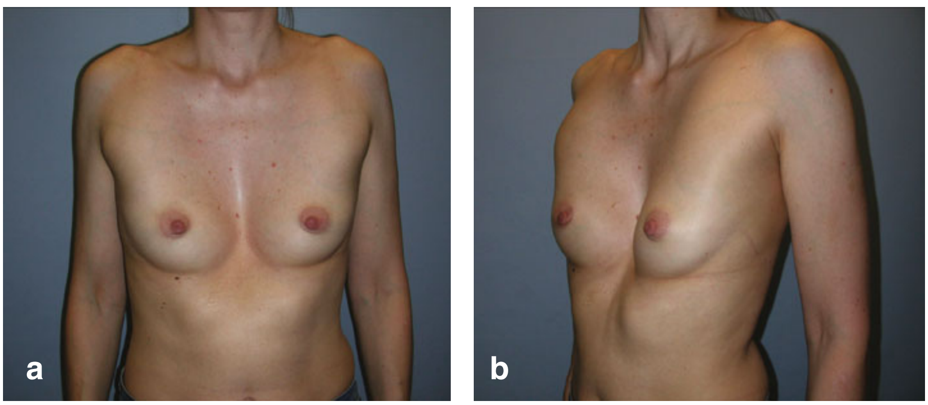

Fig. 4. Preoperative 2-D photography of a symptomatic 42-year-old female patient undergoing pectus excavatum correction with half open Nuss procedure and sternal osteotomy: **a** frontal and **b** oblique view of the anterior thoracic wall contour deformity

implant was created (Fig. 2d). Afterwards a preoperative 3-D surface scan of the patient's anterior chest wall was accomplished without and with attached moulage designed silicone implant (Fig. 2a and b). Both 3-D models were superimposed and a so-called 3-D compare with color-coded visualization of the existing differences of the two 3-D surface scans to each other was carried out (Fig. 2c). In a second step the preoperative 3-D surface

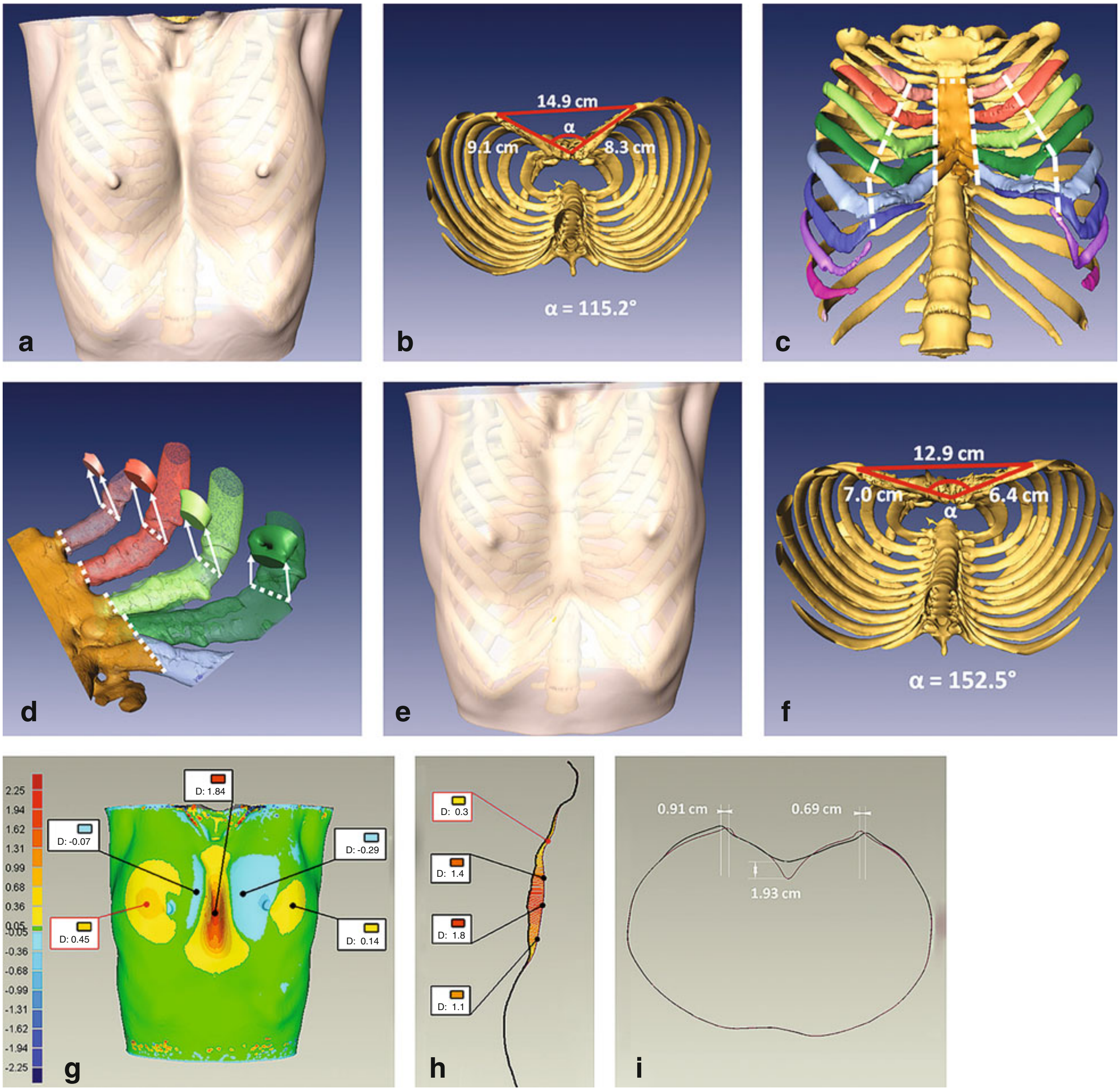

Fig. 5. Computer-aided planning of surgical thoracic wall deformity correction using 3-D CT scan data: **a** preoperative 3-D model of skin surface and deformed bony thoracic wall; **b** preoperative 3-D reconstructed bony thorax with linear and angle measurements of the deformation; **c** preoperative 3-D bony thorax with marked osteo- and chondrotomy excision lines (white dashed lines); **d** quantification of the excised osteotomy segments; **e** 3-D model of skin surface and 3-D bony thorax after virtual correction; **f** 3-D reconstructed bony thorax with linear and angle measurements after virtual correction; **g** 3-D comparison of the virtual corrected versus preoperative 3-D CT skin surface model; **h** quantification of thoracic wall shape change between pre OP (—) versus corrected 3-D CT skin model (—) using color-coded sagittal 2-D deviation slice at height of the sternum and **i** using horizontal 2-D deviation slice at height of the nipple-areola-complex. All measurements in cm (© CAPS/Brossmann)

scan (Fig. 2a) was interactively modeled using specific 3-D morphing systems (Fig. 2e). The postoperative soft tissue change for the reconstruction of the bony contour deformity after silicone implant correction is directly modeled intuitively on the virtual 3-D model by the surgeon and can be precisely quantified and visualized (Fig. 2f). The precise volume and the correct shape of a conventionally designed silicone implant can also be virtually designed (Fig. 2g). The virtually designed implant models may serve as basis for patient specific, custom-made implant design using modern manufacturing techniques for example rapid prototyping [15].

Using the example of a female patient (age: 42 years, height: 178 cm, weight: 70 kg, PSI: 2.5) with symptomatic cardiopulmonary compromised pectus excavatum (Fig. 4), the computer-aided surgical planning of chest wall repair with the semi-open Nuss technique, combined with horizontal sternum osteotomy is presented (Fig. 5). Additionally to the 3-D surface scan in standing position (Fig. 1) a preoperative CT scan of the patient in supine position with raised arms was accomplished. By means of specific software the bones and cartilages of the thorax were segmented, three-dimensionally reconstructed and a 3-D virtual model of the skeletal thorax with overlying soft tissue was created (Fig. 5a and b). The degree of the skeletal deformity can now be measured on the virtual 3-D model (Fig. 5b). Specific software functions now enable to virtual osteotomy the deformed thorax and to cut precise slices on instantly the medial and lateral cartilage border (Fig. 5c and d). Already preoperatively the dimension of the osteo- and chondrotomy and the size of excised bony or cartilage segments can be defined (Fig. 5d).

The sternum can be virtually elevated to the desired plane of the rib cage and the resulting alterations can be exactly measured (Fig. 5f). The resulting deformity of the overlying soft tissue (Fig. 5e) is interactively corrected using the above described virtual 3-D morphing software (Fig. 2e). The degree of the surgical correction

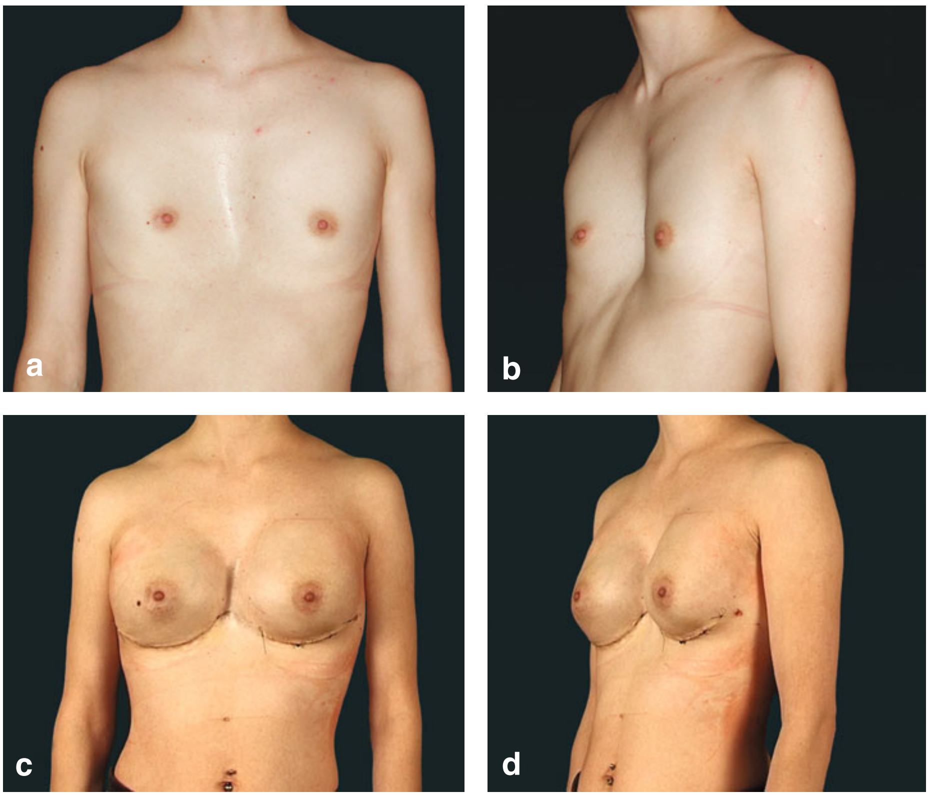

Fig. 6. Preoperative and postoperative 2-D photography of a symptomatic 23-year-old female patient undergoing pectus excavatum correction with Hegemann procedure and combined mamma augmentation: **a** preoperative frontal and **b** preoperative oblique view of the anterior thoracic wall deformity; **c** postoperative frontal and **d** postoperative oblique view of the reconstructed and augmented anterior thoracic wall

is quantified and visualized with the aid of a 3-D comparison and 2-D deviation slices (Fig. 5g–i). The resulting deformity of the thoracic wall and the overlying soft tissue can be defined already preoperatively and also can be used as a supportive and additional device intraoperatively.

13.1.4 Clinical application

Using the example of a female patient (age: 23 years, height: 158 cm, weight: 51 kg, PSI: 2.6) suffering from pectus excavatum deformity with combined mamahypoplasia (Fig. 6) a more sophisticated analysis of the postoperative outcome on the basis of the 3-D surface scan data is performed. The patient underwent thoracic wall reconstruction with Hegemann technique and combined mammary augmentation with breast expander-prosthesis for continuous filling and soft tissue expansion. Beside the 3-D quantification of the pre- and postoperative shape changes, the degree of thoracic wall correction combined with breast expander implantation and the soft tissue expansion is differentiated (Fig. 7).

For 3-D quantification of breast shape changes the pre- and postoperative 3-D scans (Fig. 7a and d) were superimposed and a color-coded 3-D shape difference was accomplished (Fig. 7c). The changes of the breast shape on a horizontal slice (Fig. 7c) and the sternal elevation in a sagittal slice (Fig. 7e) of the pre- versus postoperative superimposed 3-D surface scans can be analyzed. The lateralization of the nipple-areola-complex caused by the thoracic contour correction and soft tissue augmentation is clearly detectable (Fig. 7e). Postoperatively the implanted expander was continuously filled, before and after every expansion a 3-D surface scan of the breast region was performed to document the soft tissue change over time (Fig. 7f). At every expansion step the infiltrated volume was correlated with the breast volume increase and surface skin expansion

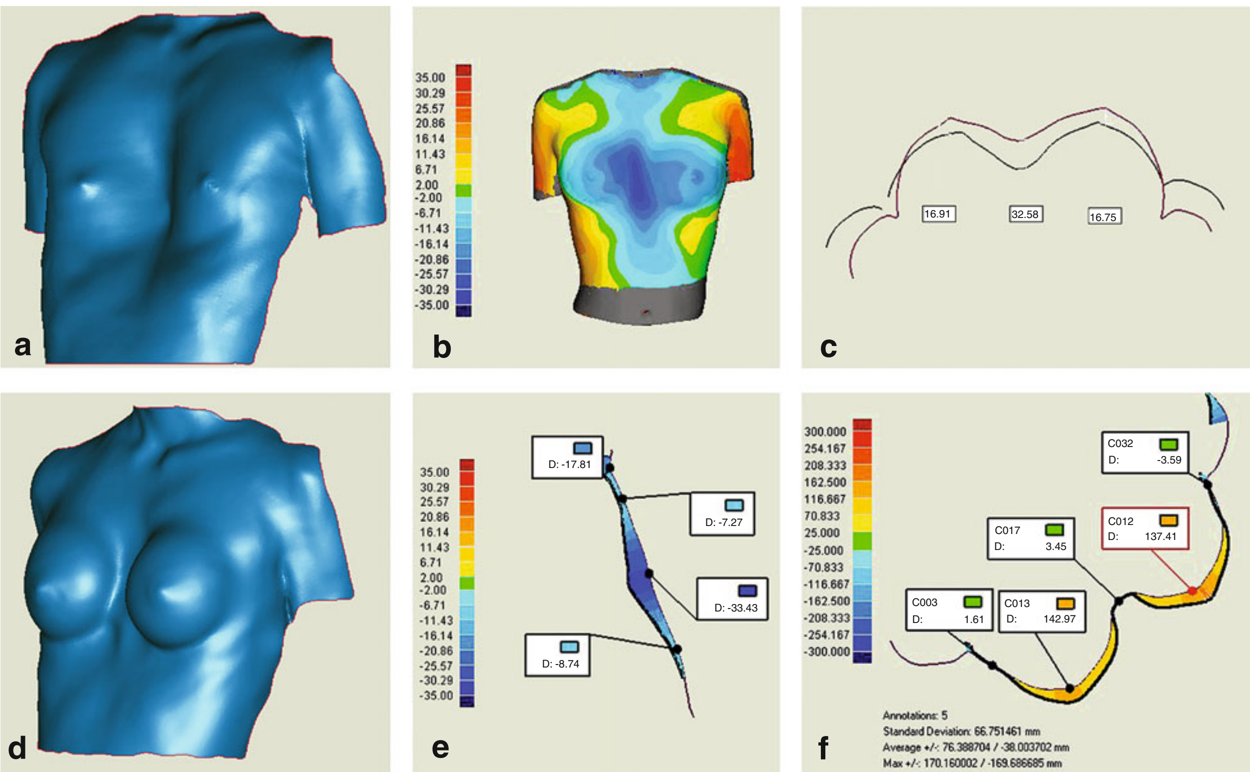

Fig. 7. Quantification of chest wall and breast changes of surgical pectus excavatum correction with simultaneous implantation of breast expander-prosthesis and postoperative soft tissue expansion: **a** preoperative 3-D surface scan; **b** color-coded quantification of 3-D chest wall shape change pre- versus postoperative 3-D scan; **c** color-coded breast shape change after surgical correction before first expansion; **d** postoperative 3-D surface skin after prosthesis expansion; **e** sagittal color-coded 2-D deviation of midsternal contour change pre- versus postoperative; **f** horizontal color-coded 2-D breast shape change after multiple expansions. All measurements in mm

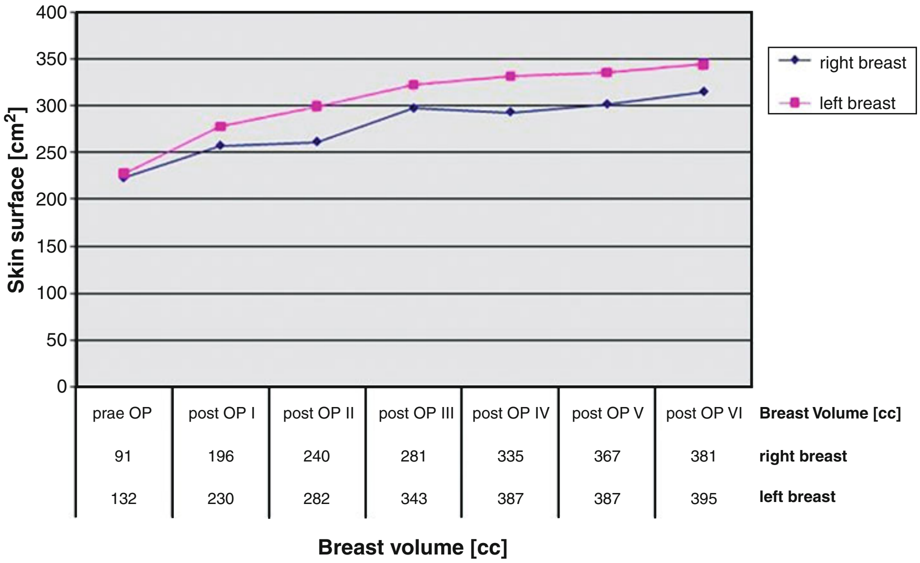

Fig. 8. Quantification of the breast skin surface expansion (cm^2) depending on the breast expander volume (cc) at different post OP expansion dates

according to the breast expander volume (Fig. 8). With the aid of this continuously 3-D quantification a precise and objective analysis of the relation between the breast expander volume and the resulting skin surface expansion is feasible. Beside a precise postoperative documentation over time and a postoperative quality assurance of the surgical outcome, this close interval quantification provides the surgeon with objective data to determine the planning and date of a potential implant exchange.

13.1.5 Conclusion

Particularly with regard to conventionally used 2-D photography the pros of 3-D surface imaging are enormous. Especially the example of computer-aided planning of a custom-made silicone implant using 3-D morphing systems demonstrates the considerable benefit of the 3-D imaging technique. In contrast to the common moulage technique with the patient in supine position, 3-D planning can be performed with the patient standing. With the patient in supine position the overlying soft tissue above the sunken sternum is deformed differently compared to the standing position, in which the true deformity is presented more realistically. However the 3-D intuitive modeling of the surface contour is limited as well. The true skeletal thoracic wall contour on which a designed implant will be placed, is masked by the overlying soft tissue during surface measurement. Therefore efforts have been undertaken to design custom-made implants using CT data taking this soft tissue coverage into account [13]. But this technique is limited by its radiation burden, time and cost intensive assessment and soft tissue change during the assessment (Fig. 9).

Optical 3-D scanning systems allow static 3-D surface geometry assessment. The clinical example of the computer-aided correction of the pectus excavatum repair with the semi-open Nuss procedure with combined osteotomy shows that the required thoracic contour changes and the degree of the performed osteotomy are preoperatively quantifiable and the aspired results can be predicted (Figs. 4 and 5). But the actual 3-D geometric prediction does not take the biomechanical properties of the human tissue into account. A surgeon will surely gain benefit from a tool that enables precise preoperative planning of the size and extent of resection at bone and cartilages, but the resulting interaction between the elevated thoracic bone and the overlying soft tissue cannot yet be simulated perfectly. The solely 3-D interactive modeling without taking biomechanical soft tissue parameters into account provides the surgeon with reasonable intuitive surgical planning information, but delivers only supportive objective measurements and thus the experience of the surgeon is still essential for the result. Therefore one cannot refer to 3-D surface scanning and modeling as surgical simulation. By

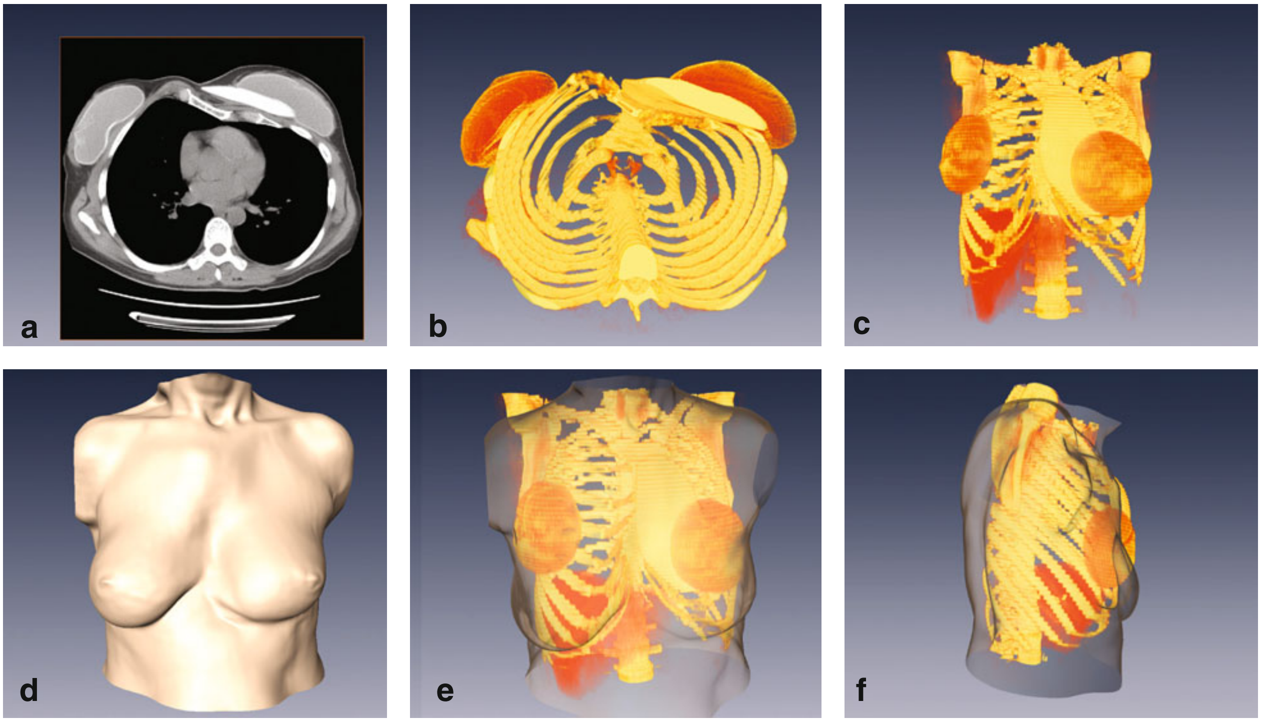

Fig. 9. Patient obtained surgical pectus excavatum correction using thoracic wall silicone implant and breast implants: **a** CT scan in supine position with implant localization; **b** 3-D supine CT data visualization of the implants view from below and **c** view from in front; **d** patients 3-D surface scan in upright position; **e** 3-D visualization of the soft tissue deformation and resulting implant upward localization between 3-D CT data in supine position and superimposed 3-D surface scan data in upright position view from in front and **f** from lateral right side (© CAPS/Brossmann)

definition a virtual simulation presumes faithful description and reproduction of biological processes using mathematical and physical precise models which can be transferred to reality.

To optimize numerically correct simulations it would be necessary to implement physical soft tissue parameters in the existing mathematical models to consider tissue elasticity and stress conditions. The implementation of these factors in the reconstructive surgical planning and to talk about a realistic virtual simulation by definition will be the challenge of future research activities in the field of 3-D imaging. First approaches can be found in the field of finite element method, which allows to mathematically calculate biomechanical processes with the aid of a numerical 3-D simulation model. Efforts to simulate the soft tissue deformation after complex osseous remodeling can be found in cranio-maxillo-facial surgery with very promising results [6]. To improve surgical techniques in the future it will be necessary to combine the results of different acquisition methods (CT/MRI and 3-D surface scans) in multi modal concepts, which contain information regarding tissue consistence and specific characteristics.

As consequence for the future clinical routine a standardized acquisition position and procedure must be maintained. Especially when combining CT/MRI data and 3-D surface scan data sometimes considerable difficulties are encountered. The reason for this problem is the different body position during acquisition. During the CT/MRI patients are in supine position with resulting soft tissue deformities, which causes extreme contour changes in the female breast region compared to the standing position during 3-D surface scanning (Fig. 9). The degree of the position depending soft tissue deformation must be analyzed and simulated before correct biomechanical surgical simulations can take place.

Altogether the advancements of the 3-D technology for surface assessment of the human body surface enter unchartered territory to quantify shape and volume changes of the human body. The currently available optical systems permit adequate precise and accurate 3-D visualization of the human body and on the one hand facilitate the surgeons estimation and planning of the extent of surgical correction of severe and complex defects and on the other hand the communication with the patient regarding potential limitations and objectives of a desired result. Although the research results with 3-D imaging data are very promising, these methods have to be validated with larger patient collectives before introducing it as a routine tool in clinical evaluation. However the empirical and intuitive estimation of an experienced surgeon will never be totally replaced by modern technologies, but such techniques and developments can support teaching or comprehensibility for patients.

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13.2 Special instruments, technical refinements

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All measurements which intend to repair a pectus deformity nowadays are aimed to utilize techniques as minimally invasive as possible to avoid growth disturbances during childhood [6] and extensive scarring in adults likewise. Such late complications were ascribed earlier [6, 14] resulting from extensive mobilization of thoracic wall tissue and forced remodeling procedures during childhood. Nowadays many studies are available that deal with large series of experience and long-term follow-up particularly in children with the MIRPE and similar techniques. Since the advent of the MIRPE technique [15, 16] many minor modifications and refinements were developed, also major ones for the application in adults (MOVARPE). To describe all advantageous or potentially also adverse new techniques would definitely exceed the scope of this book.

Herewith exemplarily listed special instruments and refinements shall just show up the progress of development. Even these, among many others, highlighted techniques may be overcome in the near future and replaced by other refinements, which will be elaborated based on creative findings, further long-term experiences, and scientific work worldwide.

13.2.1 Round tunnelizer

In the MIRPE technique initially large clamps were used as a tunnelizer or as an introducer for the intrathoracal and retrosternal manipulation in children [15, 16]. By development of particularly refined instruments for the specialized pectus excavatum repair, a strap like tunnelizer/introducer was designed, with a minor size for children and a major sized and reinforced one for adolescents (Fig. 1a–c). Such reinforced tunnelizers definitely alleviated the passage through the thoracic cavity and as a further advantage due to their robust features they allowed intraoperative remodeling of the anterior thoracic wall by preliminary elevation prior to and sequently alleviating the final transthoracal retrosternal passage of the pectus bar.

By further extensions of the application of the MIRPE technique to athletic adolescent and adult patients, problems with rigidity of the matured skeleton arose. The inelastic adult ribs rather rigorously withstand the introducing forces of metal hardware, thus increased manipulation strength must be applied for their passage leading to shearing forces along the rib edges. Such undue violence with an edged instrument will definitely damage the subcostal neurovascular structures as well as the intercostal muscles with periosteum (Fig. 2a and b). Furthermore, intrathoracally shearing forces with edged hardware retrosternally may damage the internal thoracic vessels with resulting hemorrhage [26]. In order to circumvent such potential complications particularly

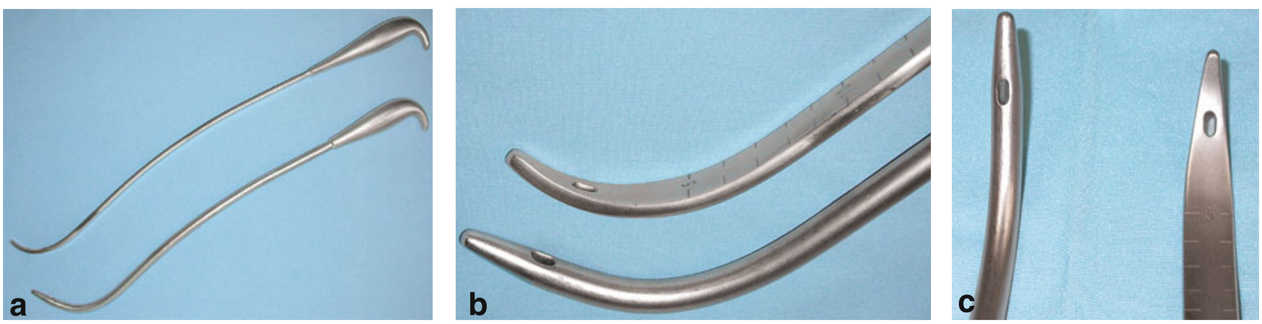

Fig. 1a–c. Comparison of two different types of tunnelizers. The flat one shows edges, which however are slightly rounded but are able to disrupt vessel and nerves at the intercostal or parasternal area. The round one is lesser prone to cause shearing-off effects of tissue from bones during intrathoracic manipulation

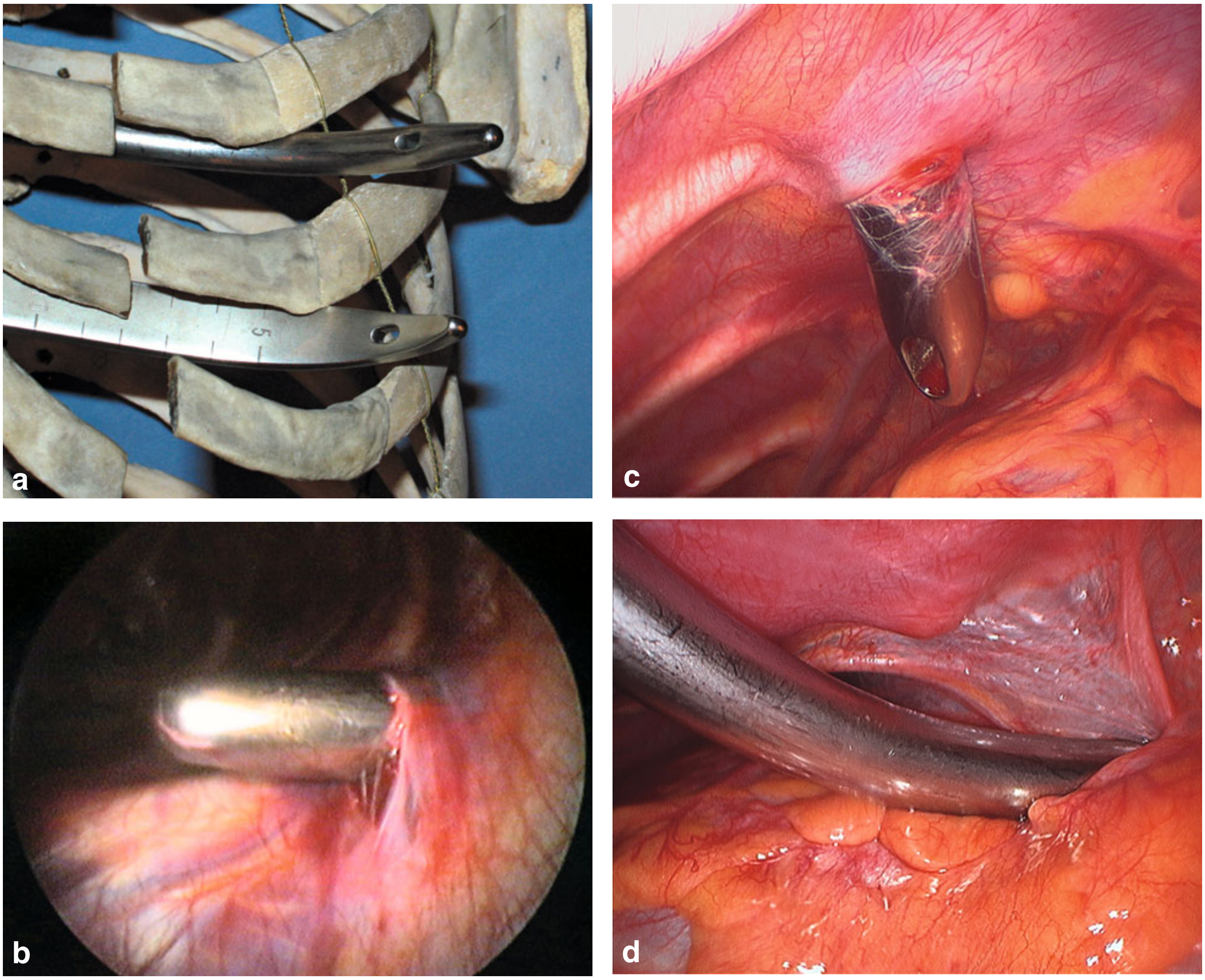

Fig. 2a. Skeletal specimen to depict the beneficial round shape of the rounded tunnelizer (above) versus the edged at one intercostal space below. **b, c** VATS view at the moment of perforation of the tunnelizer into the thoracic wall at the intercostal muscles, the round tip is closely passing the intercostal vessels and nerve without traumatization. The perfectly round tip and round shape allows for blunt perforation thus minimizing any bleeding at the thoracic wall. **c** The round tunnelizer by its advantageous shape avoids damage to the internal thoracic vessels (in the rear left from the tip of the instrument). **d** Dissection of the mediastinal and pericardial fat (below the instrument) from the sternum with gentle fan-shaped movements and loose contact to the posterior surface of the sternum

in adult patients, a rounded dissector was developed. The perfectly round diameter (Fig. 2c–e) only hardly might damage any structures along its passage between ribs retrosternally.

13.2.2 Angled oscillating saw

Such a specially shaped saw (Fig. 3a) is advantageously used for osteotomies with an access along a long subcutaneous tunnel (Fig. 3b) that can be placed at a lower thoracic region, when no space for osteosynthesis manipulation is required. In order to provide a proper survey of the osteosynthesis site furthermore an angled retractor with attached cold light source is used. Such modified retractors, frequently used in breast augmentation surgery may be very hepful in females with surgical acces from the submammary crease (Fig. 3b).

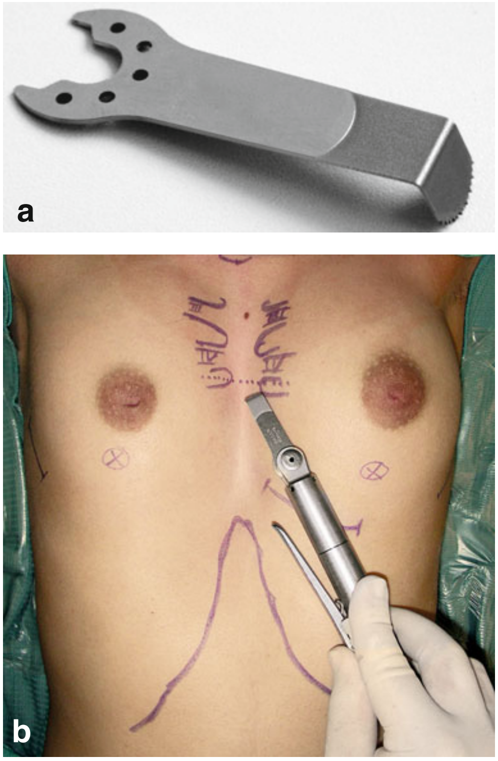

Fig. 3a. Angulated saw blade to be used at an oscillating driller for horizontal incisions at the sternum. **b** Saw instrument held in place to demonstrate the advantageous use of an angulated saw via subcutaneous access from the inframammary crease to the sternotomy site

13.2.3 Extrapleural pectus bar

Schaarschmidt in 2005 described a variant in the retrosternal and intrathoracal passage of the pectus bar. In up to 90% of cases an extrapleural positioning of the pectus bar should be feasible thus reducing the common complications associated with the MIRPE technique, namely pneumothorax, pleural effusion, and pain. By that the routine use of chest tubes was also diminished to a minimum. It may be expected that pleural adhesions ensuing to such extrapleural passage are reduced to zero, thus redo operations or required thoracoscopic interventions due to other reasons are not complicated by intrathoracal scars [21]. However, such manipulations require experience and improved technical skill with endoscopic procedures and prolong the surgery time for several minutes. Its effort on the other hand seems to be justified and worthwhile with respect to the reduction of typical early and late complications of pleural lesions.

13.2.4 Pectus bar fixation

Several refinements with the fixation procedure of the lateral wings of a pectus bar are described, using lateral stabilizers either of metal or of bioabsorbable material [19, 28]. Furthermore several kinds of wires [29, 31], sutures, or threaded alloplastic material are used in different institutions depending on the requirements of fixation forces and personal experiences with different materials. However, no statistical data can describe or propagate any material with superior characteristics and properties above others, with respect to acting as an optimal device for every kind of application. Almost every material so far described and experienced contains a list of advantages and disadvantages (Table 1), on which the performing surgeon has to rely on and select the appropriate one adapted to the individual require-

Table 1: Different characteristics of a variety of fixation devices for the pectus bar wings

Material	Advantage	Disadvantage	
Metal stabilizer	Stable fitting to the pectus bar	Palpable bulk, intra- and perimuscular scarring, difficult to remove	All kind of circumcostal suturing is prone to damage of the intercostal neurovascular bundles; the more rigid the suture the more the probability of vessel and nerve strangulation
Bioabsorbable stabilizer	Stable fitting to the pectus bar, auto-absorption	Palpable bulk, may break, increased wound infection rate, intra- and perimuscular scarring, costs	
PDS® sutures	Strong suture with long-term absorption	Thread knot-ends may be palpable for months	
Mersilene® band	Very strong device	Not absorbable	
Metal Wire	Very rigid fixation to the ribs feasible	May breake and migrate into the thorax	

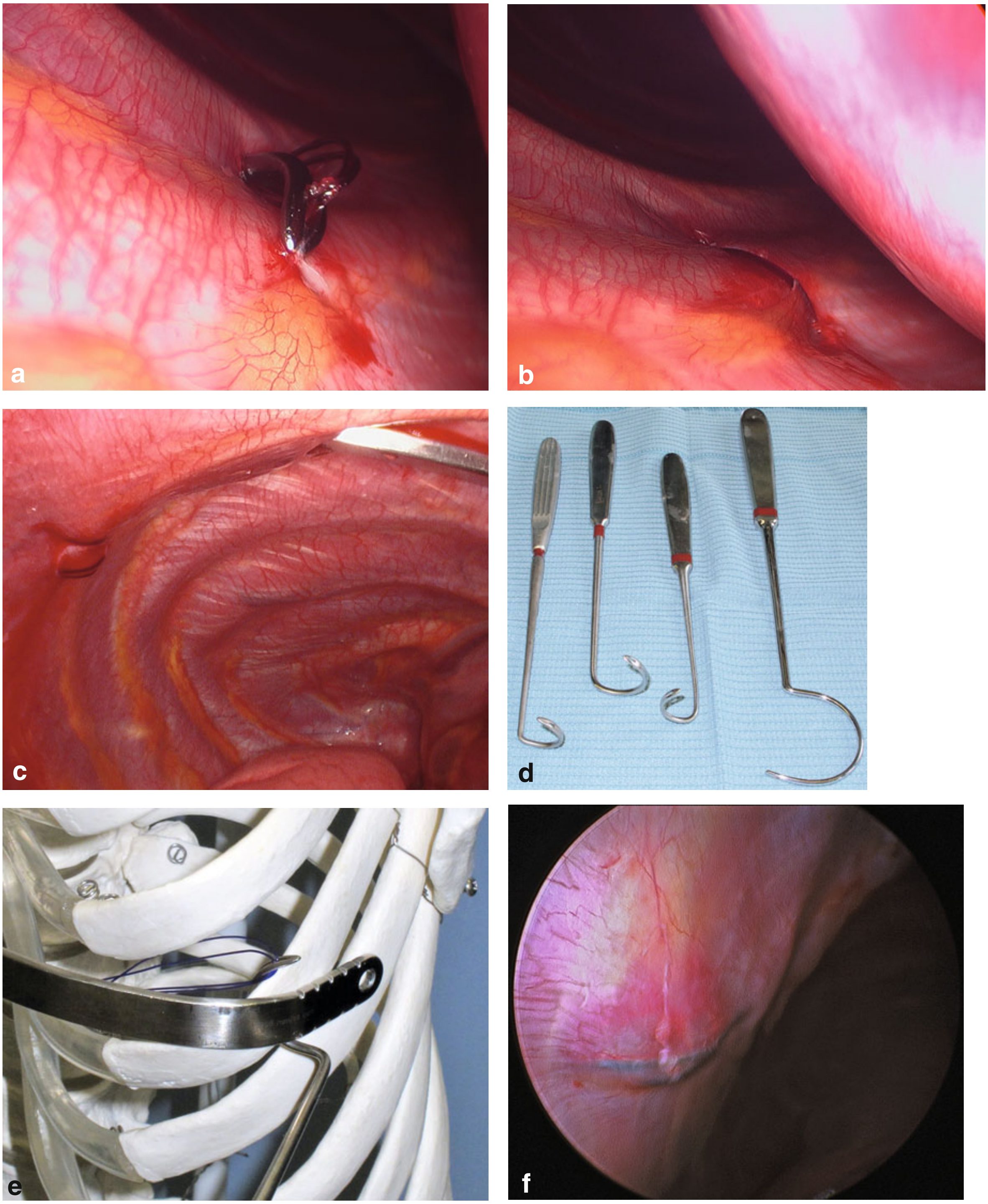

Fig. 4a. VATS view at a PDS threaded Deschamps needle just passing the inner surface of the rib. **b** Completion of circumcostal suture seen at the lateral thoracic wall. **c** Overview within a right thoracic cavity and deflated lung. Notice the pectus bar at the anterior thoracic wall in situ (above), its lateral wing fixed with two circumcostal PDS sutures (left side at picture). **d** Deschamps ligation needles with different shapes for the pectus bar fixation. The angled ones serve for lateral fixation, the straight and large one (right) for parasternal access. **e** Skeletal specimen to depict the course of the Deschamps needle with suture around the rib and attached pectus bar wing. **f** Subpleural course of the Deschamps needle to avoid damage to the pleura thus minimizing complications

ments of the patient. If ever feasible, a three-point fixation [17, 30] in patients beyond childhood, that is an additional fixation at the parasternal region should be performed, which is feasible anyhow, when an additional central surgical acces (MOVARPE) is applied.
Such pericostal or better described as circumcostal fixation with exemplarily PDS sutures may be achieved with several devices available [7, 20, 29, 30]. Ideally the fixation procedure, that is the circumcostal, transmuscular, and endothoracal passage of the threaded instrument is guided and surveyed with the aid of endoscopic view (Fig. 4a–c). A Deschamps ligature device with a blunt tip is available in different shapes (Fig. 4d) for variable accesses to the ribs laterally (Fig. 4e) and in the parasternal region to place the sutures around the ribs. Care herewith has to be taken to avoid lesions of the neurovascular intercostal bundles during the needle passage and only loose knotting is recommended to prevent the intercostal nerve, running within the subcostal groove from strangulation. Demanding some skill, the circumcostal passage may even stay at the extrapleural space (Fig. 4f) thus minimizing pleural adhesions through the surgical trauma or bleedings into the pleural cavity, potentially derived from lesion of the intercostal vessels [21].

13.2.5 Hybrid repair

Modified approaches utilizing the MIRPE technique in combination with minor- or semi-open (MOVARPE) access seem to further establish its right for application in cases with major deformities with sternum malrotation, asymmetry or in adolescent and adult cases with thorax rigidity. The elevation and ensuing alleviated support of deeply sunken sternum in extensive and/or asymmetric funnel chest deformities must be preceeded by multiple relaxing incisions at the sternum and parasternal rib cartilages, occasionally also by wedge resections and chondrectomies. Minor cutaneous incisions at the preseternal region may accompany the incisions needed for the MIRPE access, but compared with conventional open techniques the hybrid access still is of minor invasiveness with reduced pain due to reduction of the forces needed to overcome the rigidity of an exemplarily athletic thorax or of tall and bodily matured patients (Chapter 6.4).
As a refinement of such a hybrid access in the pectus excavatum repair, multiple relaxing- or so-called kerf incisions were applied by Al-Assiri et al. [1] from inside the thorax under endoscopic view in order to relax the anterior thoracic wall prior to the pectus bar implantation maneuver. The outcomes were not different in terms of aesthetics or function, but the intraoperative view during the intrathoracal maneuvers was definitely improved, thus providing increased security to avoid lesions in thoracal organs. In addition, a relaxed anterior thoracic wall will alleviate the retrosternal passage of instruments and pectus bar thus reducing the necessity of undue forces during their implantation.

13.2.6 Absorbable plates and screws

Although widely used in craniofacial surgery [9] but to a limited extent in the throacic wall repair [4, 11–13, 25], they still do not provide with the same stability as does metal hardware with respect to bending forces, which have to resist against forces after anterior chest wall remodeling. The resistance to longitudinal strain however is similar to those of metal mini-plates with the major advantage of complete absorption after 1 year. On the other hand, such elastic properties follow the micromovements at the sternum osteosynthesis during respiration, thus behave like a dynamized nailing concept with resulting stimulus to form callus for fracture healing by secondary intention. Usually with an oblique and subcutaneous access a perfectly tight osteosynthesis enabling primary fracture healing in the sternum region is not feasible due to limited survey and limited space for surgical maneuvers in the pectus deformities repair with predomonantly aesthetic claim. The loss of resistance from slowly proceeding absorption takes place far beyond the time of completed biological fracture healing [9, 11], so that temporary stabilization with such material suffices the requirements of the remodeling repair at the sternum. However, plates and screws will not at all provide stability at strained cartilages and should not be utilized at the ribs instead of ideally applied strong reefing sutures.

13.2.7 Absorbable lateral stabilizer

Lateral stabilizers with different styles (Fig. 3a in Chapter 6.9) were and still are widely used as an adjunct to avoid tilting of the pectus bar. In order to circumvent cumbersome maneuvers and tissue dissection for the purpose of pectus bar removal (Chapter 6.9), absorbable stabilizers have been developed. Such absorbable devices represent an interesting development in order to reduce the surgical trauma and life quality during and after a pectus bar removal procedure. However, they are prone to show more complications in terms of device fracture or wound infection at the site of implantation compared with the metal ones [19, 28]. On the other hand, several authors already abandoned the use of lateral stabilizers at all, since they preferably rely on measurements using minor volumes of foreign material but apparently improved statics by three point fixations with sutures, wires, or other threads to successfully avoid tilting of the pectus bar [7, 29].

13.2.8 Klobe's vaccum bell

When a patient due to several reasons decides against a pectus bar suspension but in favor for the conventional technique according to Ravitch in the repair of pectus excavatum, one could utilize the vacuum bell after Klobe (Chapter 6.8) as an additional supporting device. Such a measurement starting several days postoperatively may maintain the position of the surgically elevated sternum, which by the conventional technique is held in place only by sutures and eventually osteo-

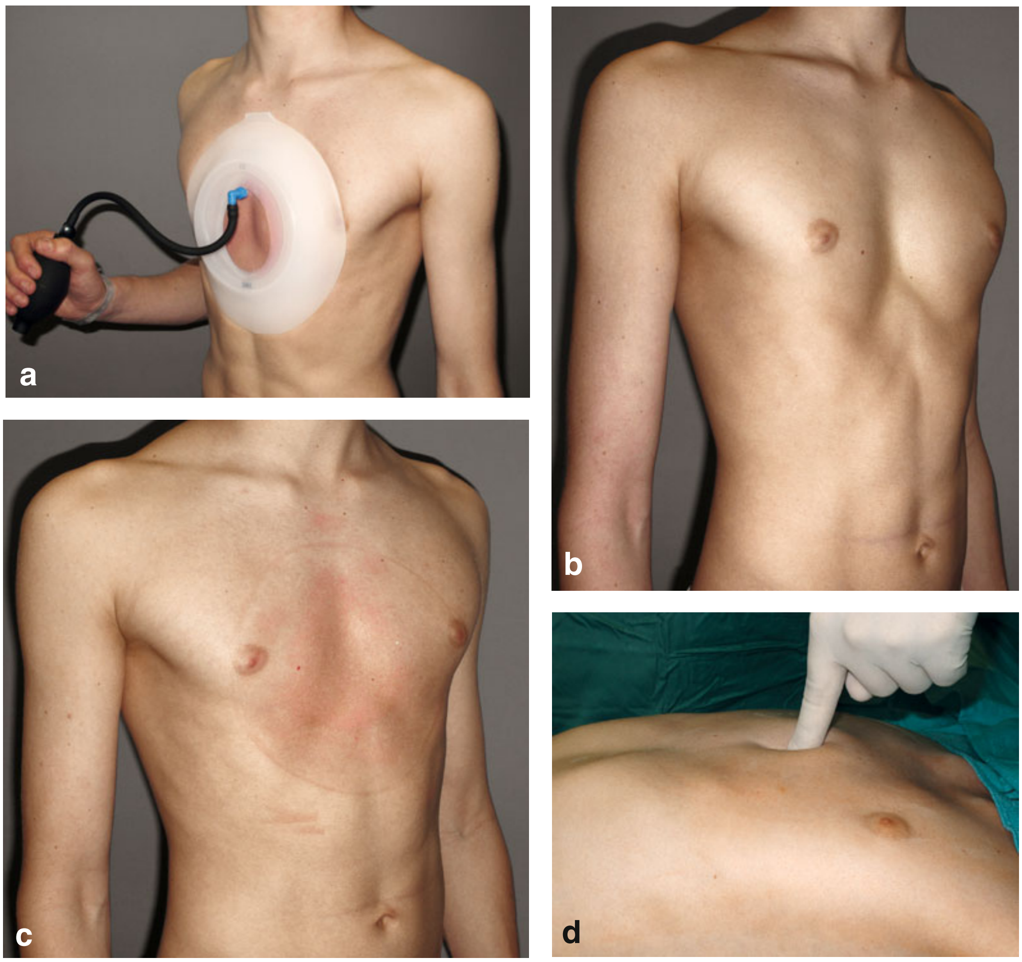

Fig. 5a. Vacuum bell after Klobe is applied to enhance the volume of the soft tissue at the presternal region during a short-term period of application. It may also be used as an intraoperative adjunct to elevate the sternum during and for the purpose to alleviate surgical access with retrosternal passage. **b** and **c** Pretreatment situation of a moderate pectus excavatum deformity (**b**). Situation with temporary tissue augmentation achieved only by several single applications of the vacuum bell (**c**). **d** Intraoperative situs, the anterior thoracic wall is pretreated with the vacuum bell for 3 weeks to moderately elevate the sternum as an assistance to alleviate the retrosternal passage of instruments and pectus bar during the MIRPE procedure. Notice the additional side effect of tissue augmentation by edema, demonstrated by the sunken finger, in fact prepared and suitable for a lipofilling procedure. However, the patient with this pretreatment successfully underwent MIRPE

synthetic plates. Through the negative pressure the natural forces to regain the original shape of a sunken sternum might be overcome to stabilize the long-term result therewith (Fig. 5a).

There is however no such application yet described in the available literature. The original purpose of the application of the vacuum bell to an untouched and surgically untreated thoracic wall is to achieve an elevation of the sunken sternum to ventral, overcoming the naturally present forces of disfigured sternum and cartilages [2, 5, 23]. It would be plausible and understandable therefore that a thoracic wall surgically weakened by osteochondrotomies can be held in position or, as an aesthetic advantage, can even be elevated slightly out from the surgically feasible level of elevation. This maneuver by such a negative pressure device therefore appears much easier then than without surgery to achieve a permanently pleasing result. Certainly the compliance of the patient in the postoperative weeks must be ensured herewith. The duration of such an ancillary treatment would be 2–3 months until a stable consolidation of the cartilages and reefed periosteal tubes as well as the osteosynthesis is achieved.

The vacuum bell applies to a technique that is used in the breast augmentation also, named the BRAVA technique. Herewith the negative pressure applied to underdeveloped female breasts is used to augment their volume gradually and over the duration of several months [24, 27]. A recent refinement consists therein that preexpansion of breast tissue by negative pressure just for several weeks leads to volume augmentation by edema and enhancement of vascularization. Into such altered tissue lipofilling is then applied in order to permanently achieve tissue augmentation by improved conditions for the implanted lipocytes to survive. However, such reports are singular yet and series with more patients treated are not available. From a logical point such an enhancement of vascularization and subcutaneous volume by negative pressure within a funnel chest depression (Fig. 5b–d) as a priming for ensuing lipofilling might be a valuable tool to improve the late results of lipofilling in the delicate presternal region.

13.2.9 Endoscopic and thoracoscopic repair in pectus carinatum

This seems to be a promising development in terms of reduction of major presternal scars and pains that result from the invasiveness of the common open access [10, 22]. Partial resection of abundant length of rib cartilages seems to be feasible from a thoracoscopic approach in unilateral pectus carinatum deformities [10]. If the sternum is involved, the technique after Schaarschmidt, using a subpectoral but endoscopic access may be applied to reduce invasiveness and postoperative morbidity compared to a conventional open access.

Hock in 2005 used the MIRPE technique in a reverse manner to repair pectus carinatum deformities in a small series with convincing results so far [8]. The depression of the protrusion of sternum is managed by implantation of a pectus bar above the sternum and is supported by intrathoracal “sublay” of the pectus bar wings bilaterally along the thoracic wall flanks, which are elevated therewith.

However, these preliminary series of minimally invasive endoscopic pectus carinatum repair so far has not yet provided long-term results, furthermore ensuing studies are not available.

13.2.10 Lipofilling

Already described in Chapter 6.6.2 this topic is new and so far only preliminary experiences and publications exist in the application to thoracic wall deformities [18]. The long-term results in the application at other than pectus anomaly sites are promising and further development is still proceeding. One major issue for the application at the central sternal region is the fact that only a thin subcutaneous layer exists with low vascularization, into which lipotransfer may be applied. The relatively strong adhesion of skin to the sternum impedes the injection of fat and its survival, since pressure is well known to inhibit ingrowth of transplanted fat. It might therefore be wise to apply lipofilling predominantly at lateral thoracic wall depressions or in combination with vacuum bell application in advance [3].

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