Eur J Echocardiography (2002) **3,** 67–72
doi:10.1053/euje.2001.0129, available online at http://www.idealibrary.com on IDEAL®

Quantitative Assessment of Right Ventricular Volumes in Severe Chronic Thromboembolic Pulmonary Hypertension using Transthoracic Three-dimensional Echocardiography: Changes due to Pulmonary Thromboendarterectomy

T. Menzel[1], T. Kramm[2], A. Brückner[1], S. Mohr-Kahaly[1], E. Mayer[2] and J. Meyer[1]

[1]*2nd Medical Clinic (Department of Cardiology);* [2]*Clinic for Cardiothoracic and Vascular Surgery, Johannes Gutenberg University, Langenbeckstrasse 1, D-55101 Mainz, Germany*

Aims: Evaluation of a three-dimensional reconstruction method to show the changes of right ventricular volume and systolic function when patients undergo pulmonary thromboendarterectomy for chronic thromboembolic pulmonary hypertension.

Methods and Results: In the examination of 11 patients (four female, seven male; age 56 ± 10 years) before and after pulmonary thromboendarterectomy, end-diastolic and end-systolic right ventricular volumes were determined as a sum total of the calculated volumes of derived parallel slices of the right ventricle. Using a Tomtec workstation and a Vingmed CFM 800 echocardiography device, the acquired data were ECG-and respiration-triggered in the course of transthoracic examination, using step intervals of 5°. The ventricular outline was traced manually on 5 mm slices from longitudinal cut planes. For subsequent correction, their area measurements were displayed and the volume cross-checked against the volume from orthogonal cut planes.

End-diastolic and end-systolic volumes could be quantified in 11/11 cases before surgery, but data could only be attained for 9/11 patients after surgery, because a limited apical window rendered the postoperative three-dimensional reconstruction impossible in two cases. Before surgery, right ventricular size was larger than normal and systolic function was clearly impaired in all of the patients (end-diastolic volume: 121 ± 37 ml; end-systolic volume 91 ± 30 ml; ejection fraction $25 \pm 8\%$). The decrease in mean pulmonary artery pressure after surgery was significant (47 ± 8 vs 26 ± 8 mmHg; $P<0{\cdot}.05$). End-diastolic and end-systolic right ventricular volumes had been reduced (80 ± 33 ml and 54 ± 31 ml respectively), and the ejection fraction had increased ($36 \pm 9\%$).

Conclusions: Successfully performed pulmonary thromboendarterectomy leads to a significant reduction of right ventricular chamber size and improvement of systolic function, which can be determined with great precision and quite easily, using transthoracic three-dimensional echocardiography.
(Eur J Echocardiography 2002; 3: 67–72)

Key Words: chronic thromboembolic pulmonary hypertension; pulmonary thromboendarterectomy; three-dimensional echocardiography.

Introduction

Chronic thromboembolic pulmonary hypertension causes right ventricular pressure overload, which leads to functional and morphologic alterations of the right ventricle. As has been shown previously for pulmonary thromboendarterectomy, however, the haemodynamic and cardiac changes remain partially reversible even

Address for correspondence: Dr. med. Thomas Menzel, MD, Weichselstrasse 14, D-81677 Munich, Germany. Tel: ++49/178/2092699; Fax: ++49/611/691177; E-mail: menzel@mail.uni-mainz.de

Received 16 July 2001; revised manuscript received 17 October 2001; accepted 17 October 2001

1525-2167/02/010067+06 $35.00/0

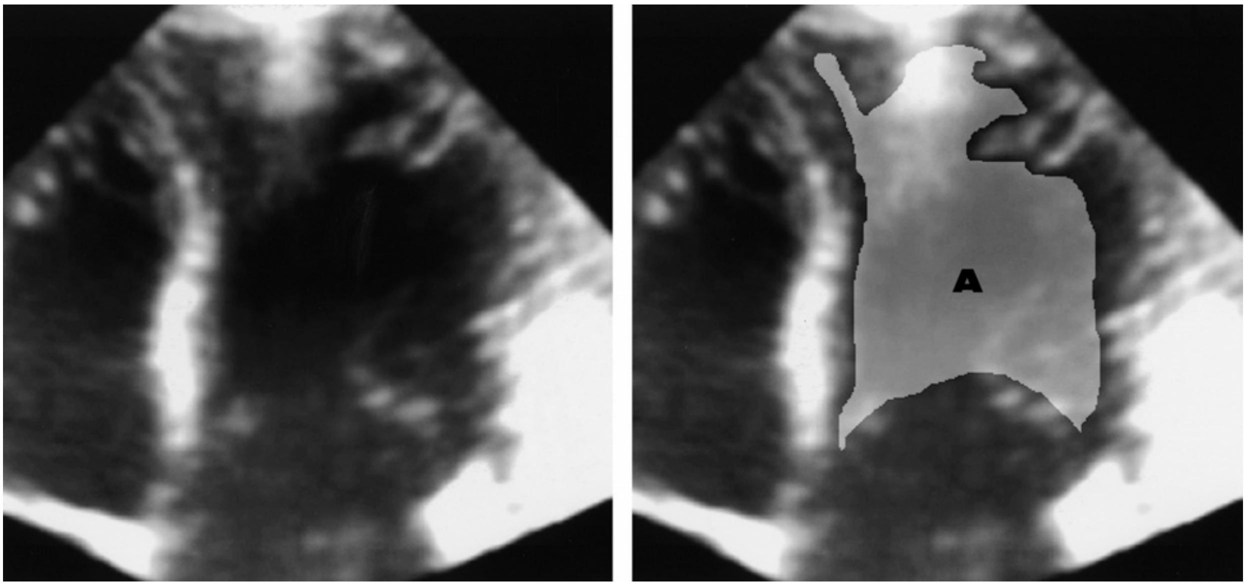

Figure 1. Left, a two-dimensional cut plane of both ventricles. Right, an identical plane, where the border of the endocardium has been traced (A).

after years of illness[1–12]. The change in right ventricular dimensions can be used to assess the success of pulmonary thromboendarterectomy, but quantification by two-dimensional transthoracic echocardiography using planimetry in the apical four-chamber view is known to be difficult and sometimes impossible. Three-dimensional echocardiography is a new diagnostic tool that can be applied to determine ventricular volume, reconstructing the ventricle from a three-dimensional data set. We investigated the applicability and variability of three-dimensional echocardiography in the determination of right ventricular function and geometry, examining patients with chronic thromboembolic pulmonary hypertension before and after pulmonary thromboendarterectomy.

Methods

Study Patients

Eleven patients (four female, seven male; mean age 56 ± 10 years; age range 30–69 years) undergoing pulmonary thromboendarterectomy were included in the investigation. The mean duration of symptomatic pulmonary hypertension was 56 ± 46 months. Patients were examined 20 ± 12 days before and 12 ± 6 days after surgery. All patients were in sinus rhythm.

The criteria for offering pulmonary thromboendarterectomy were a mean pulmonary artery pressure greater than 300 $dynes \times s \times cm^{-5}$, thromboembolic lesions considered surgically accessible (main, lobar, or segmental arteries), NYHA functional class III and IV, and unsuccessful anticoagulation therapy over a 6-month period.

Surgical Procedure

The endarterectomy of pulmonary arteries was performed with a standardized technique using extracorporeal circulation, deep hypothermia and circulatory arrest periods[13–15]. None of the patients underwent additional tricuspid valve repair.

Two-dimensional Echocardiography

Two- and three-dimensional echocardiography were both performed with standard techniques, using commercially available equipment (Vingmed CFM 800 with a mechanical transthoracic probe, 2·5 MHz (Vingmed Sound, Horten, Norway)). Images were obtained with the patients in left lateral position. During the two-dimensional examination, measurements were taken in end-expiration.

The right ventricular end-diastolic (RV-EDA) and end-systolic (RV-ESA) cavity areas were determined planimetrically in the apical four-chamber view. Fractional area change was calculated as: RV-FAC= (RV-EDA–RV-ESA)/RV-EDA × 100[16].

Three-dimensional Echocardiography

In all of the 11 study cases data for three-dimensional measurements could be acquired during the transthoracic examination, for which a TomTec workstation with a 133 MHz Pentium processor (TomTec Imaging System, Boulder, CO, USA) was connected to the Vingmed CFM 800 ultrasound system with transthoracic mechanical probe (2·5 MHz). A four-chamber

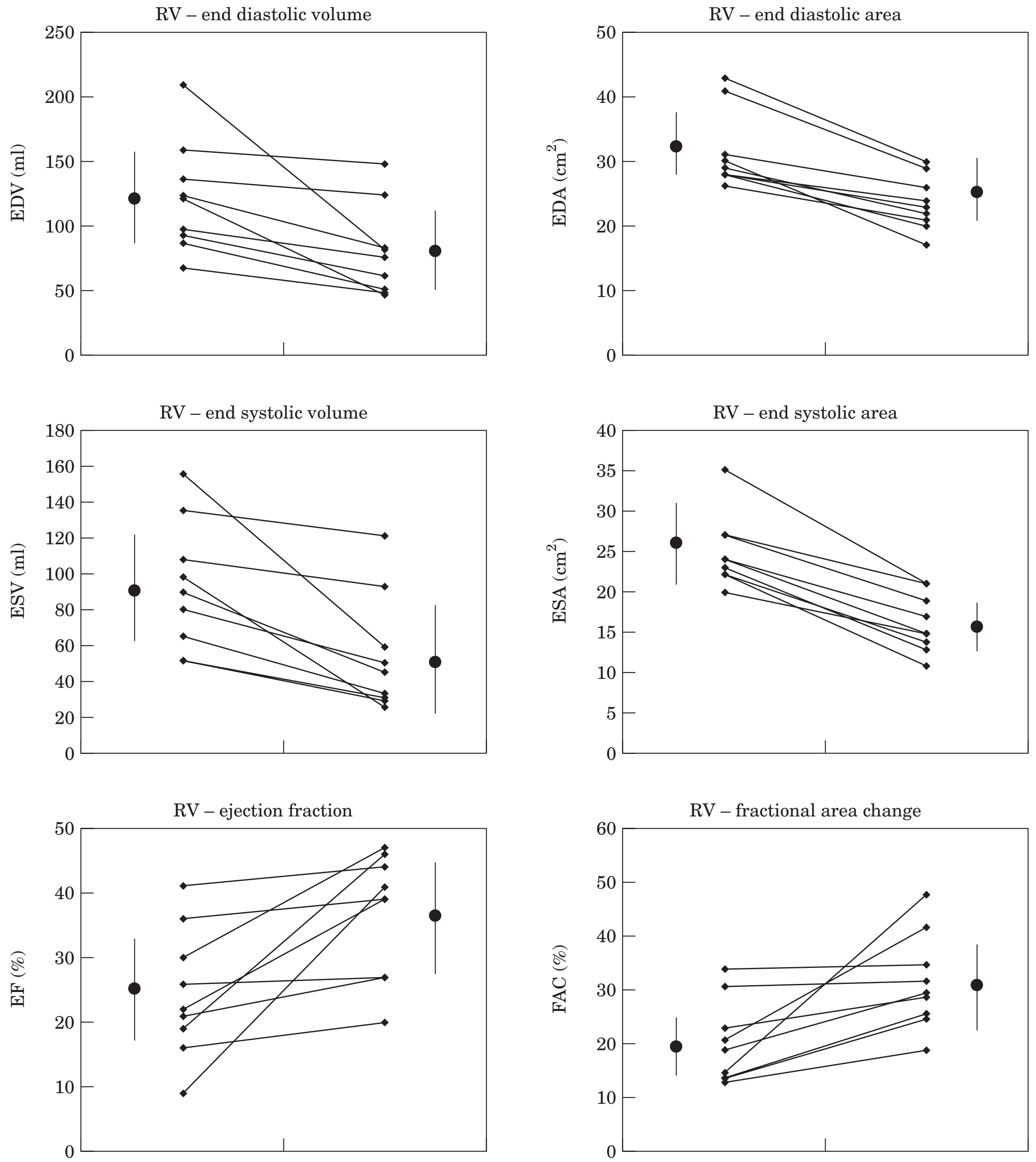

Figure 2. Postoperative changes in right ventricular size and systolic function, determined using the three-dimensional technique (left-hand) and the two-dimensional technique (right-hand).

view was visualized for the acquisition of data, whereby the acquisition of three-dimensional data was accomplished by mounting the probe to a carriage device. With the use of a step motor, a rotational movement of the transducer could be effected in discrete increments commanded by a software-based steering logic. A regular three-lead ECG was monitored continuously, and respiration was monitored by skin impedance measurement. Cardiac cycles had to be of a pre-selected length and respiratory phase to be chosen for three-dimensional data acquisition.

To fill the conic data volume, the transducer was made to execute a rotational movement covering 0° to 180° with a step interval of 5°. A complete cardiac cycle was recorded at each step before the step motor rotated the transducer to the next cross-section. After finishing

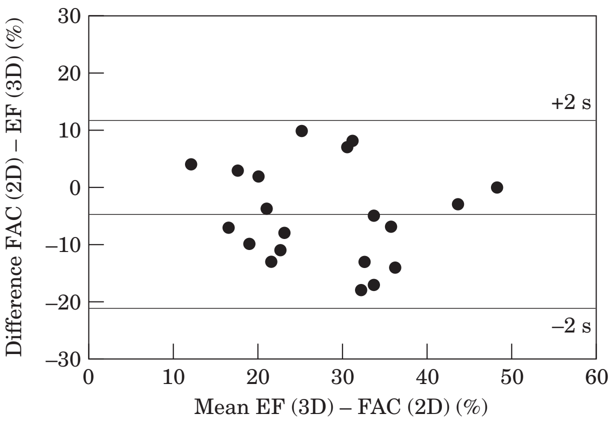

Figure 3. Two-dimensional fractional area change (FAC-2D) vs three-dimensional ejection fraction (EF-3D). Plot of the difference against the mean (Bland and Altmann). The mean difference is −4·8%, limits of agreement amounting to −21·2% and +11·6%.

one complete scan and before storing, data were calibrated using the online ultrasound image. Subsequent processing procedures were conducted offline, without the patient.

Together with the first loading of raw data sets, a post-processing was performed by the computer in which it converted the recorded sequences of two-dimensional images into a volumetric data set.

Planimetric Determination of Right Ventricular Volumes

After selecting the long axis view of the right ventricle, end-diastolic (defined as the peak of the R-wave of the QRS complex) and then end-systolic (defined as the first frame before opening of the tricuspid valve) volumetric data sets were selected. Right ventricular volumes were calculated by manually tracing along the endocardial border in sequential long axis cut planes throughout the ventricle, from ventral to dorsal at 5 mm intervals (Fig. 1). Once endocardial tracing of the long axis planes had been completed, the slice volume was calculated by summing the voxels included within the traced area in 5 mm slice thickness.

To yield both end-diastolic and end-systolic right ventricular volumes the system then added up the corresponding subvolumes slice by slice. After this first step, the investigator selected the short axis of the ventricle out of the volumetric data set, and the system displayed its orthogonal view. Now sequential short axis views were shown of the ventricle in 5 mm slice intervals from the tricuspid annulus to the apex, and endocardial border tracings from the first step of the calculation could be corrected manually, if necessary. Papillary muscles were excluded from the right ventricular volume.

Right ventricular ejection fraction was calculated as follows: ejection fraction = (end-diastolic volume–end-systolic volume) ÷ (end-diastolic volume × 100). The process of volume determination was done two times for each patient.

Cardiac Catheterization

Pre- and postoperative haemodynamic measurements were undertaken with the use of a Swan–Ganz catheter to determine the pulmonary artery pressure and pulmonary vascular resistance for all of the patients.

Statistical Methods

Data processing was performed using the Statistical Analysis System (SAS) version 6.12. Variables obtained by two-dimensional echocardiography were averaged from three distinct measurements for each patient. Volumes determined by three-dimensional echocardiography were averaged from two distinct measurements for each patient. Continuous variables were expressed as mean ± 1 SD. Pre- and postoperative continuous variables were compared by the Wilcoxon signed-rank test. A P value $<0{\cdot}05$ was considered to be statistically significant.

Variability of Three-dimensional Determined Volumes

Intra-observer variability was assessed in terms of reproducibility. One and the same observer always did two determinations of any volume measurement (end-diastolic and end-systolic, pre- and postoperative). Then variability was described as the mean and the range of absolute differences over all measured pairs. Inter-observer variability was described by the mean and range of absolute differences of pairs measured by two different observers.

Results

Two-dimensional Echocardiography

In all of the patient cases the parameters in question could be determined with satisfactory accuracy. But in one case, a limited apical window rendered two-dimensional echocardiography impossible after surgery.

Measurements of the right ventricular area before surgery showed enlargement in all cases (end-diastolic area: 33 ± 5 cm^2; end-systolic area: 26 ± 5 cm^2). Systolic function was impaired (fractional area change: 20 ± 6%). After surgery, the mean end-diastolic area and the mean end-systolic area of the right ventricle had both been reduced (24 ± 4 cm^2 and 16 ± 3 cm^2 respectively). The systolic function had improved in all patients (fractional area change: 31 ± 8%). The changes were all of statistical significance (Fig. 2).

Three-dimensional Echocardiography

A three-dimensional data set could be acquired with satisfactory accuracy for all of the patients before surgery, but after surgery the right ventricular volume could not be determined in two of the cases. Pre-operative measurements showed increased right ventricular volume in all patients (end-diastolic volume: 121 ± 37 ml; end-systolic volume: 91 ± 30 ml), and systolic function was impaired (ejection fraction: 25 ± 8%). On examination after surgery, both volumes had decreased (end-diastolic volume: 80 ± 33 ml; end-systolic volume: 54 ± 31 ml), and systolic function had improved (ejection fraction: 36 ± 9%) (Fig. 3). All of these changes were statistically significant.

Variability of Three-dimensional Measurements

For all together 40 volume pairs the mean absolute difference found between the first and second measurements taken in only one plane (first analysis) amounted to − 1·05 ml (range from − 16 to + 13 ml). The mean absolute difference between the first and the second measurement of the 40 volume pairs determined after correction of the first step and using the second plane (second analysis) amounted to − 2·35 ml (range from − 17 to + 10 ml).

The mean absolute difference of the 40 volume pairs measured by two independent observers (comparison of measurements taken only in one plane) amounted to − 1·9 ml (range from − 18 to + 14 ml).

Haemodynamic Variables

Mean pulmonary artery pressure and pulmonary vascular resistance were elevated in pre-operative measurements. After pulmonary thromboendarterectomy, a marked decrease could be demonstrated (47 ± 8 vs 26 ± 8 mmHg; $P<0.05$).

Discussion

Chronic pulmonary hypertension results in a marked dilatation and impaired systolic function of the right ventricle. As has been shown previously[11,12], pulmonary thromboendarterectomy effects a significant decline in right ventricular afterload, which results in a rapid decrease of right ventricular size and improvement of the systolic function. Therefore, the accurate measurement of both right ventricular size and function is desirable in patients undergoing PTE. However, there are two aspects of the right ventricular anatomy which make it difficult to assess volume and function using two-dimensional echocardiography: the ventricle's complex shape, and a heavy trabeculation of the free wall which almost always complicates edge recognition.

Three-dimensional echocardiography at least partially overcomes the difficulties in determination of volume and function which are caused by the complex structure of the ventricle, because a three-dimensional echocardiographic data set contains, and can be made to depict, the entire right ventricle over the whole heart cycle. Within this data set, two-dimensional cross-sections can be displayed and they can be rotated on three different axes, and parallel planes can be chosen. This allows calculation of the right ventricular volumes and function without geometric assumptions. Three-dimensional echocardiography has already been shown to provide accurate measurements of left and right ventricular volumes and function[17–19]. However, no study has ever evaluated the practicality of this technique in assessing changes of right ventricular function and volumes in patients undergoing pulmonary thromboendarterectomy.

With the use of two-dimensional echocardiography, this study fundamentally demonstrated a reduction of right ventricular size and improvement of the right ventricular function after surgical correction of pulmonary hypertension. The main findings, however, were as follows:

(1) Three-dimensional echocardiography makes it possible to determine right ventricular volumes.
(2) After surgical correction of pulmonary hypertension (pulmonary thromboendarterectomy), a reduction of right ventricular size as well as improved systolic function can be detected by way of a three-dimensional technique, and here these changes could be confirmed and documented with the two-dimensional planimetric technique.
(3) The difference was marginal between volume measurements derived from longitudinal cut planes and measurements obtained after correction of the ventricular borders in an additional plane.

To determine ventricular volumina with a summation of slices, we did endocardium border tracings in the longitudinal axis of the right ventricle, rather than the summation of orthogonal slices used by other working groups. One would expect that our technique might be problematic where the cut planes selected for planimetry lie close to the ventricular wall, assuming that this could cause substantial measuring errors. However, the results of our work show that there was actually only a very slight deviation between two measurements of the same ventricle in one cut plane, and that correction of the endocardium border in a second, orthogonal cut plane did not raise the rate of variability. On the contrary, the overall variability of measured values sank slightly. Neither could the examiner show any significant deviation between endocardium borders that were drawn in the first step of the analysis and those determined in the second step. We conclude from this that planimetry of the right ventricle is possible in both longitudinal and orthogonal cut planes.

Limitations

One possible limitation to the conclusiveness of our statistical analysis is the small study population; a larger cohort would strengthen the impact. Both the area and the volume measurement techniques are echocardiographic methods and for that they are susceptible to the limitations that accompany use of an ultrasonic signal. Both methods are also dependent on the subjectivity of a human operator tracking the endocardial border. In spite of that, however, there was no great variability of measurements with the three-dimensional technique.

The comparison of right ventricular fractional area change (2D) with ejection fraction (3D) in this study also demands explanation: it was done only to demonstrate that three-dimensional echo shows postoperative change matching that found by the 2D method. The main problem we saw in our investigation was the lack of a method to compare volumes determined by three-dimensional echo to the findings of e.g. MRT or radio nuclide ventriculography.

Clinical Implications

For questions of right ventricular volume determination, three-dimensional echocardiography provides promising aspects well beyond the conventional two-dimensional examination. Three-dimensional echocardiography overcomes the difficulties in determination of volume and function caused by the complex shape of the ventricle and allows reconstruction of right ventricular volumes and function without geometric assumptions.

Acknowledgements

We thank Mr R. Meinert, PhD, Institute for Statistics and Documentation, Johannes Gutenberg University of Mainz, Germany for statistical data processing. Thanks also to Ms Joy Christensen, InternationalMeetingPoint joysuechr@get2net.dk for English language advice.

References

[1] Moser KM, Fedullo PF. Acute and chronic pulmonary thromboembolism. In Peacock AJ, ed. *Pulmonary Circulation* — A handbook for clinicians. London: Chapman & Hall, 1996: 400–422.

[2] Moser KM, Spragg RG, Utley J *et al.* Chronic thrombotic obstruction of major pulmonary arteries. *Ann Intern Med* 1983; **99:** 299–305.

[3] Moser KM, Auger WR, Fedullo PF. Chronic major-vessel thromboembolic pulmonary hypertension. *Circulation* 1990; **81:** 1735–1743.

[4] Jamieson SW, Auger WR, Fedullo PF *et al.* Experience and results with 150 PTE operations over a 29-month period. *J Thorac Cardiovasc Surg* 1993; **106:** 116–127.

[5] Mayer E, Dahm M, Hake U, *et al.* Thromboendarterectomy in chronic thromboembolic pulmonary hypertension. Hemodynamics and right-heart function over the long term. *Dtsch med Wschr* 1996; **121:** 9–15.

[6] Iversen S. Surgical treatment of thromboembolism-induced pulmonary hypertension. *Z Kardiol* 1994; **83** (Suppl 6): 193–199.

[7] Simonneau G, Azaria R, Brenot F *et al.* Surgical Management of unresolved pulmonary embolism. *Chest* 1995; **107:** 52S–55S.

[8] Rasmussen CM, Dyer D, Wheeler K *et al.* Automatic border detection to assess right ventricular function following surgical treatment of thromboembolic pulmonary hypertension. *Echocardiography* 1996; **13:** 109–116.

[9] Klepetko W, Moritz A, Burghuber OC *et al.* Die chronisch-thromboembolische pulmonale Hypertension und ihre Behandlung mit der pulmonalen Thrombendarteriektomie. *Wien Klin Wochenschr* 1995; **107:** 396–402.

[10] Hartz RS, Byrne JG, Levitsky S *et al.* Predictors of mortality in PTE. *Ann Thorac Surg* 1996; **62:** 1255–1260.

[11] Chow LC, Dittrich HC, Hoit BD *et al.* Doppler assessment in right-sided cardiac hemodynamics after PTE. *Am J Cardiol* 1988; **61:** 1092–1097.

[12] Dittrich HC, Nicod PH, Chow LC *et al.* Early changes in right heart geometry after PTE. *J Am Coll Cardiol* 1988; **11:** 937–943.

[13] Daily PO, Dembitsky WP, Peterson KL *et al.* Modifications of techniques and early results of PTE for chronic pulmonary embolism. *J Thorac Cardiovasc Surg* 1987; **93:** 221–233.

[14] Iversen S, Mayer E, Schmiedt W *et al.* Das chirurgische Konzept der pulmonalen Thrombendarteriektomie. *Z Herz Thorax Gefäßchir* 1993; **7:** 23–28.

[15] Mayer E, Kramm T, Dahm M *et al.* Aktuelle Frühergebnisse nach pulmonaler Thrombendarteriektomie bei chronischer thromboembolischer pulmonaler Hypertonie. *Z Kardiol* 1997; **86:** 920–927.

[16] Kaul S, Tei C, Hopkins JM *et al.* Assessment of right ventricular function using two-dimensional echocardiography. *Am Heart J* 1984; **107:** 526–531.

[17] Nosir YFM, Salustri A, Kasprzak JD, Brebuda CS, Ten Cate FJ, Roelandt JRTC. Left ventricular ejection fraction in patients with normal and distorted left ventricular shape by three-dimensional echocardiographic methods: a comparison with radionuclide angiography. *J Am Soc Echocardiogr* 1998; **11:** 620–630.

[18] Kupferwasser I, Mohr-Kahaly S, Stähr P *et al.* Transthoracic three-dimensional echocardiographic volumetry of distorted left ventricles using rotational scanning. *J Am Soc Echocardiogr* 1997; **10:** 840–852.

[19] Papavassiliou DP, Parks WJ, Hopkins KL, Fyfe DA. Three-dimensional echocardiograpic measurement of right ventricular volume in children with congenital heart disease validated by magnetic resonance imaging. *J Am Soc Echocardiogr* 1998; **11:** 770–777.