Res Exp Med (2000) 199:333–340

Research in
Experimental Medicine
© Springer-Verlag 2000

One-lung flooding for video-assisted thoracoscopic surgery in animal experiments on pigs – oxygenation and intrapulmonary shunt

S. Klinzing[1], T. Lesser[2], H. Schubert[3], M. Bartel[2], U. Klein[1]

[1] Klinik für Anästhesiologie und Intensivtherapie, Friedrich-Schiller-Universität Jena, Bachstrasse 18, D-07740 Jena, Germany
[2] Department of Thoracic and Vascular Surgery, Friedrich Schiller University of Jena, Jena, Germany
[3] Institute of Animal Experimentation of the Friedrich Schiller University of Jena, Jena, Germany

Received: 19 June / Accepted: 19 November 1999

Abstract. Unilateral flooding of the lung after intubation with a double-lumen tube makes intraoperative sonography of the lung during video-assisted thoracoscopic surgery possible. After flooding with 15 ml/kg, the arterial partial oxygen pressure (with FiO_2=1.0) is higher than that in total atelectasis by about 100 mmHg, while it is only slightly less than that during bilateral lung ventilation. Compared to total atelectasis, lung flooding reduces the pulmonary right-to-left shunt volume. The pulmonary function normalizes within 8 h after the operation.

Key words: Bronchoalveolar flooding – Thoracoscopy – Lung sonography – Hemodynamics – Oxygenation

Introduction

The operative strategy in pulmonary tumour surgery is decisively influenced by the exact presentation of the size, extension and location of the tumour. Intraoperative sonography of the lung could, in this respect, be a valuable addition to other diagnostic tools. Because of sound reflection by the air content, lung sonography with conventional techniques, even with atelectasis of one lung, does not provide useful information. Therefore, we have developed the technique of unilateral flooding, which makes the lung accessible to complete sonographic examination [9]. With conventional thoracotomy and thoracoscopic surgery, changes in haemodynamics, gas exchange

Correspondence to: S. Klinzing; E-mail: sklinzing.an.bacm.ukj@anae1.med.uni-jena.de, Fax: +49-3641-933441

and intrapulmonary shunt volume are sufficiently known, whereas observations of the effects of unilateral flooding on gas exchange are meagre and limited to therapy for pulmonary alveolar proteinosis [7].

This report describes how experimental unilateral lung flooding under conditions of video-assisted thoracoscopic surgery affects gas exchange and the intrapulmonary shunt volume and how it influences the pulmonary function in the postoperative phase.

Material and methods

The animal experiments were carried out on seven young "Deutsches Landschwein" female pigs (weight range: 30–39 kg, average: 34.6 kg).

Experimental procedure

Anaesthesia was initiated by an intramuscular injection of 10 mg/kg ketamine (Ketanest) with 150 IE hyaluronidase (Hylase). Additionally, following cannulation of an ear vein, 6.25 mg dehydrobenzperidol (Droperidol) and 10 mg diazepam were administered. During spontaneous respiration, orotracheal intubation was performed (left-bend Robertshaw double lumen tube with extra-long bronchial leg, model 39 Ch, specially made by Mallinckrodt, Athlone, Ireland). Correct positioning of the tube was verified by flexible bronchoscopy (Olympus BF 3C30 fibre bronchoscope). After relaxation with 50 mg rocuronium bromide (Esmeron) and deepening of the anaesthesia by a dose of 0.2 mg fentanyl, artificial ventilation was commenced with 1–1.5 MAC of isoflurane in pure oxygen (FiO_2=1.0). Anaesthesia and relaxation were maintained by continuous application of the inhalation anesthetic and regular follow-up injections of 20 mg rocuronium bromide and 0.1–0.2 mg fentanyl. Respiration under volume control was provided by an intensive respirator (Siemens Servo 900; tidal volume 10 ml/kg, respiratory rate 16–20 cycles/min, expiratory partial CO_2 pressure 35–45 mmHg, PEEP=6 cm H_2O). A base infusion, 4–6 ml/kg per hour whole electrolyte solution and 2–4 ml/kg per hour hydroxyethyl starch (HES 10%) were infused. Body core temperature was kept between 36°C and 37°C by warming the infusion solutions and covering the animals with heat-insulating foil.

The right inguinal vessels were exposed, and an arterial catheter was introduced into the right femoral artery. A pulmonary arterial catheter (Swan-Ganz CCO/SvO_2 TD Catheter 744H7.5F, Baxter Healthcare, Irvine, USA) was introduced into the femoral vein by venesection and advanced into the pulmonary artery. Both arterial and venous catheters were applied as a subcutaneous port system.

The electrocardiogram, arterial blood pressure, capillary oxygen saturation and expiratory CO_2 concentration were measured and recorded continuously (Datex AS/3, Helsinki, Finland).

Twenty minutes after artificial respiration with an inspiratory oxygen concentration of 100% (PEEP=6 cm H_2O, V_t=10 ml/kg), a 7-mm thoracoport was applied in the left pleural cavity, followed by disconnection of the endobronchial tube-leg from the respirator. After spontaneous atelectasis, the left lung was slowly filled through the left tube-leg with 15 ml/kg of an isotonic electrolyte solution (E 153) preheated to body temperature. Filling was performed passively, utilizing the gravity of the liquid flowing from an infusion bottle suspended 50 cm above heart-level. The animal was then temporarily brought to an anti-Trendelenburg position (30°). After completion of lung flooding, the tube-end of the flooded side was hermetically sealed and the horizontal dorsal position restored. The liquid was left in the lung for 60 min. During this time, the lung was examined by transpleural and endobronchial sonography.

Lung sonography

Transpleural sonography of the lung was performed both with the atelectatic and flooded lung (sonic transducers: convex array 5.0 and 7.5 MHz; convex array laparoscopic MFI transducer 5.0/6.5/7.5 MHz; linear array MFI transducer 5.0/6.5/7.5 MHz; B&K Medical Sonographic System 3535). In addition, endobronchial sonography was performed with an ultrasonic catheter (SonyCath catheter, 12.5 MHz, 6.2 F; Boston Scientific, USA) applied through the left, liquid-filled tube-leg.

After completion of the sonographic examinations, the liquid was either aspirated with a fibrescope or drained passively in the Trendelenburg position, followed by simultaneous ventilation of both lungs. When spontaneous respiration reached a sufficient level, the animals were extubated.

Intraoperative blood gas analyses

Arterial and mixed venous blood gas analyses (ABL System 625, Radiometer, Copenhagen) were performed at defined measurement times (spontaneous respiration via double lumen tube FiO_2=1.0, anaesthesia (FiO_2=1.0, PEEP=6 cm H_2O, V_t=10 ml/kg): completion of atelectasis, 30 min after start of flooding, 60 min after start of flooding, 15 min after start of two-lung ventilation and 30 min after start of two-lung ventilation. Further laboratory diagnostic tests included blood count, electrolytes and coagulation. The pulmonary right-to-left shunt volume was calculated as follows:

$$Qs/Qt = \frac{AaDO_2 \cdot 0.0031}{(AaDO_2 \cdot 0.0031) + CaO_2 - CvO_2}$$

where $AaDO_2$ is the alveolo-arterial oxygen difference, CaO_2 the oxygen content of the arterial blood, and CvO_2 the oxygen content of the mixed-venous blood [12].

Postoperative blood gas analyses

Blood gas analyses were performed on the animals at different times after extubation. The animals were sedated by repeated injections of propofol (Disoprivan) with total doses between 80 and 160 mg. Arterialized and mixed venous blood was aspirated by percutaneous puncture of the port capsules. Blood gas analyses were obtained under spontaneous respiration of ambient air and after 20 min of artificial respiration with pure oxygen. The postoperative measuring times are shown in Table 1.

Table 1. Postoperative measuring times

Time after extubation	2 h	4 h	8 h	12 h	24 h	48 h	6 days	8 days
Animal A	x	x	x	x	x			
Animal B	x	x	x	x	x	x		
Animal C	x	x	x	x				
Animal D						x		
Animal E						x		
Animal F							x	
Animal G								x

Pressure in the respiratory passageway and flooding liquid recovery rate

The pressure in the flooded bronchial system was determined by connecting the tube-end to a pressure sensor calibrated for the heart level. The volume of aspirated or passively drained flooding liquid was measured before the start of reventilation.

Results

Haemodynamics

There were no significant changes in heart rate or arterial blood pressure during the intraoperative period.

Partial arterial oxygen pressure (PaO_2) and pulmonary right-to-left shunt volume (Qs/Qt) –intraoperative behaviour

Under total atelectasis, PaO_2 dropped to a minimum of 215.5±69.7 mmHg. Under flooding, it rose again to 397.3±90.8 mmHg, i.e. 182 mmHg above the level under total atelectasis. PaO_2 under flooding was but less than with bilateral lung ventilation, before and after thoracoscopy. Under total atelectasis, the pulmonary right-to-left shunt volume rose by 11.3% above the initial value, reaching a maximum of 28%. Under flooding, the shunt fraction dropped to 17%–19%, with no difference after reventilation Table 2).

Postoperative lung function – PaO_2 with ambient air and oxygen breathing

PaO_2 in the early postoperative phase was reduced, both with ambient air and pure oxygen breathing. The PaO_2 levels normalised after approximately 8 h. At any measuring time, PaO_2 with ambient air breathing was below the expected levels of about 90–95 mmHg (Tables 3, 4; Fig. 1).

Table 2. Intraoperative behaviour of PaO_2 and intrapulmonary right-to-left shunt volume (Qs/Qt). Data are expressed as mean values and standard deviation

Study stage	PaO_2 (mmHg)	Qs/Qt
Spontaneous respiration via double lumen tube FiO_2=1.0	370.7±44.2	0.200±0.054
Anaesthesia (FiO_2=1.0, PEEP=6 cm H_2O, V_t=10 ml/kg)	471.2±42.5	0.170±0.041
Completion of atelectasis	215.5±69.7	0.283±0.073
30 min after start of flooding	372.1±73.0	0.191±0.048
60 min after start of flooding	397.3±90.8	0.175±0.042
15 min after start of two-lung ventilation	430.2±94.1	0.169±0.038
30 min after start of two-lung ventilation	455.0±61.1	0.151±0.038

Table 3. PaO_2 with ambient air breathing

Time after extubation	2 h	4 h	8 h	12 h	24 h	48 h	6 days	8 days
Animal A		72.9	84.3	96.2	82.2			
Animal B	45.9	76.2	69.3	83.4	86.2	78.8		
Animal C	58.5	64.0	64.6	78.3				
Animal D						59.8		
Animal E						82.2		
Animal F							61.4	
Animal G								65.3

Table 4. PaO_2 with pure oxygen breathing

Time after extubation	2 h	4 h	8 h	12 h	24 h	48 h	6 days	8 days
Animal A	108.0	257.0	421.7	481.8	464.7			
Animal B	228.9	451.2	200.6	348.4	497.8	485.4		
Animal C	189.0	362.0	438.9	460.0				
Animal D						291.5		
Animal E						475.0		
Animal F							333.9	
Animal G								356.3

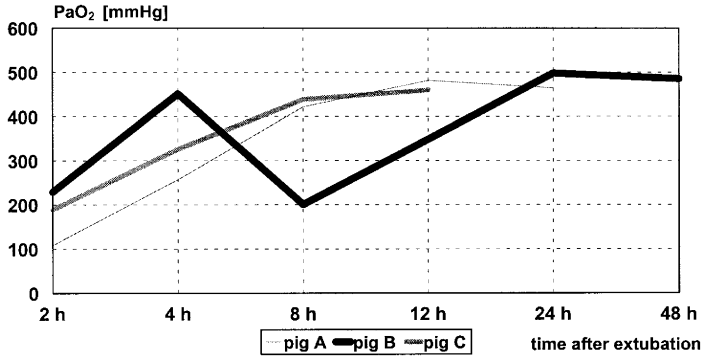

Fig. 1. PaO_2 with oxygen breathing in the early postoperative phase, compared with oxygen breathing via double lumen tube after induction of anaesthesia

Postoperative lung function – intrapulmonary shunt volume

The early postoperative phase showed an increase in the intrapulmonary shunt fraction (Table 5). Again, normalization was observed after about 8 h. Given the small number of cases involved, it did not seem meaningful to perform a significance test. In animal B (measuring time 24 h) and animal D, an intrapulmonary shunt calculation could not be carried out because of failure of the venous port system.

Table 5. Intrapulmonary shunt volume with oxygen breathing

Time after extubation	2 h	4 h	8 h	12 h	24 h	48 h	6 days	8 days
Animal A	0.444	0.308	0.232	0.183	0.146			
Animal B	0.363	0.440	0.373	0.244	–	0.132		
Animal C	0.354	0.253	0.221	0.226				
Animal D						–		
Animal E						0.234		
Animal F							0.230	
Animal G								0.241

Pressure in the respiratory passageway and flooding liquid recovery rate

With a flooding volume of 15 ml/kg body weight, the pressure in the respiratory tract was 11.0 mmHg on average (minimum 10 mmHg, maximum 13 mmHg). The rate of recovery of the flooding liquid was 60% after fibrescopic aspiration and 75–80% after passive draining.

Discussion

Localization of peripheral lung foci under conditions of video-assisted thoracoscopic surgery is very difficult. The surgeon does not here the option of bi-digital palpation, and intraoperative imaging techniques are not available for routine use. Sonographic examination of the lung parenchyma may be a promising alternative, provided the bronchial system and lung parenchyma can be completely evacuated of residual gas. In preliminary experiments we proved that sonography of the unilaterally flooded lung is suitable for the localization of intrapulmonal foci [9, 10].

In this study, we examined how unilateral lung flooding affects both oxygenation and intrapulmonary shunt volume during video-assisted thoracoscopy and postoperative lung function of normal experimental animals. Experience with unilateral flooding of the bronchial system after intubation with a double-lumen tube has been gained for three decades because of its application in the treatment of alveolar proteinosis [11], alveolar microlithiasis, acute silicosis, cystic fibrosis and after inhalation of radioactive particles [5]. It has been proved that even extensive lavages with up to 50 l of liquid are well tolerated [5].

In conventional one-lung ventilation, the combined action of gravity and the hypoxia-induced pulmonary vasoconstriction causes a redistribution of the blood flow to the dependent, ventilated lung. As this redistribution is incomplete, the shunt volume increases when the independent lung is under atelectasis and PaO_2 drops. To improve oxygenation, one can increase the inspiratory oxygen concentration. However, 10–15% of thoracoscopy patients show hypoxemia when subjected to one-lung ventilation and an inspiratory oxygen concentration of 100% [8]. By the application of a continuous positive pressure of 5–10 cm H_2O on the non-ventilated lung under insuffla-

tion of pure oxygen, PaO_2 can be increased. However, sonographic lung examination is not possible under these conditions.

Our experiment has proved that lung flooding under thoracoscopic conditions provides a distinct increase in PaO_2 compared to total atelectasis. PaO_2 in the unilaterally flooded lung corresponds approximately to that under bilateral lung ventilation prior to thoracotomy. This makes the application of pure oxygen to the independent lung under constant positive airway pressure (CPAP) unnecessary. The impressive improvement of arterial oxygenation is caused by an augmentation of the existing blood redistribution to the dependent lung. Due to the combined effect of gravity redistribution of blood flow, capillary compression due to intra-alveolar pressure of the flooding liquid, and hypoxic vasoconstriction, blood flow in the flooded lung is almost completely stopped. The airway pressure of 11 mmHg measured under flooding exceeds the pulmocapillary pressure and brings the blood flow in the independent lung to a standstill. In a previous study Doppler flow rate measurements were performed in the pulmonary arteries of thoracotomed animals, which demonstrated that pulmonary arterial flow in the flooded lung virtually ceases (publication forthcoming). An improvement in the arterial oxygen saturation (measured by pulse oxymetry) and PaO_2 has also been observed in the filling phase during bronchopulmonary lavage [4, 13].

Under total atelectasis, the pulmonary right-to-left shunt volume reached a maximum of approximately 28%. In the flooded lung, the shunt fraction dropped to 17–19%. The pulmonary right-to-left shunt volume was influenced by the same blood flow redistribution mechanisms.

In the early postoperative phase following extubation, a deterioration of gas exchange was observed. During the first 8 h post-extubation, the pulmonary function largely normalized. A possible reason for this decline in oxygenation is disturbance of the perfusion/ventilation ratio due to residual fluid in the bronchoalveolar system. As on average only 60% or 70% of the liquid originally applied was recovered by passive draining or bronchoscopic aspiration, respectively, we must assume the presence of a considerable volume of residual fluid, the complete absorption of which takes several hours. To what extent a single flooding of a lung affects its functional surfactant content will be examined in further investigations.

The relatively low partial oxygen pressures with ambient air breathing can most likely be explained by the respiration-depressive effect of propofol, the agent employed to sedate the animals. The anaesthetic chosen was isoflurane. Inhalation anaesthetics generally reduce hypoxia-induced pulmonary vasoconstriction and lead to an increase in intrapulmonary shunt volume [6]. The effect of the volatiles is complex: a combination of depressed hypoxic pulmonary vasoconstriction influencing mixed venous saturation, and impaired contractility of the myocardium affecting cardiac output. Because of the complex action of isoflurane, clinically relevant dosages are not expected to significantly reduce PaO_2 [2].

A further question avising from our study is whether the stoppage of blood flow in the pulmonary artery by prolonged one-lung flooding will lead to ischaemia-induced damage of the lung tissue.

Overall, given the small number of experimental animals, no statements on statistical significance were possible. However, we conclude from our in-

vestigations that unilateral lung flooding under thoracoscopic conditions is a favourable method to enable intraoperative lung sonography. The redistribution of blood flow to the dependent lung makes an application of CPAP to the non-ventilated lung unnecessary. In the first 8 h following extubation, the lung function of healthy animals is completely restored.

Acknowledgements. The authors wish to thank Mrs. Petra Dobermann and Mrs. Uta Reinhold at the Institute of Animal Experimentation, Friedrich Schiller University of Jena, for their valuable help. The Thuringian State Administration Office permitted the animal experiments and declared them to conform with the Animal Protection Act.

References

1. Aguinaga G, Santos P, Renes E, Alvaro PF, Lorente JA, Maudes A, Diaz RR, Landin L, Liste D (1991) Hemodynamic changes during whole bronchoalveolar lavage in two cases of pulmonary alveolar proteinosis. Intensive Care Med 17:421–423
2. Benumof JL (1986) Isoflurane anesthesia and arterial oxygenation during one-lung ventilation. Anesthesiology 64:419–422
3. Carlsson AJ, Bindslev L, Hedenstierna G (1987) Hypoxia-induced vasoconstriction in the human lung. The effect of isoflurane anesthesia. Anesthesiology 66:312–316
4. Cohen E, Eisenkraft JB (1990) Bronchopulmonary lavage: effects on oxygenation and hemodynamics. J Cardiothorac Anesth 4:609–615
5. Danel C, Israel-Biet U, Costabel U, Klech H (1992) Therapeutic applications of bronchoalveolar lavage. Eur Respir J 5:1173–1175
6. Groh J, Kuhnle GEH, Ney L, Sckell A, Geotz AE (1995) Effects of isoflurane on regional pulmonary blood flow during one-lung ventilation. Br J Anaesth 74:209–216
7. Hemstad JR, Spiess BD, Marchioro TL, Raghu G (1994) Pulmonary artery and noninvasive hemodynamics during lung lavage in primary alveolar proteinosis. Chest 105:1605–1608
8. Jedeikin R, Olsfanger D, Shachor D (1994) Intraoperative anaesthetic management of hypoxaemia during transthoracic endoscopic sympathectomy. Eur J Surg 160: [Suppl 572]23–25
9. Lesser T, Klinzing S, Schubert J, Klein U, Bartel M (1999) Lung flooding – a new method for complete lung sonography. Res Exp Med 198:83–91
10. Lesser T, Klinzing S, Schubert J, Bartel M (1999) Simulations of lung lesions for validating the sonography of the flooded lung. Res Exp Med 198:261–268
11. Ramirez RJ, Kieffer R, Ball W (1965) Broncho-bronchopulmonary lavage in man. Ann Intern Med 63:819–828
12. Shapiro BA (1988) Arterial blood gas monitoring. In: Vender JS (ed) Symposium on Intensive Care Monitoring, Critical Care Clinics 4, no 3. Saunders, Philadelphia pp 479–484
13. Tate K, Zoellner P, Bode E T (1992) Bronchopulmonary lavage for pulmonary Alveolar proteinosis. Missouri Med 89:27–30