Intensive Care Med (1990) 16:500–505

Intensive Care Medicine

Pulmonary capillary pressure and gas exchange after E. coli bacteremia in pigs

R. Fretschner, Th. Klöss, H. Guggenberger, D. Heuser, H.-J. Schmid and M. Widmann

Anesthesiology and Transfusion Medicine Division, University of Tübingen, Tübingen, FRG

Received: 12 January 1990; accepted: 12 September 1990

Abstract. In 9 Goettingen minipigs we studied the effect of E. coli bacteremia on effective pulmonary capillary pressure and the longitudinal distribution of pulmonary vascular resistance. Precapillary pressure gradient (dPa) was calculated as the difference between mean pulmonary artery pressure (MPP) and effective pulmonary capillary pressure (Pc) (dPa = MPP-Pc), postcapillary pressure gradient (dPv) as the difference between Pc and left atrial pressure (dPv = Pc-LAP). The disturbance of pulmonary gas exchange was quantified by the $AaDO_2$ quotient $1\text{-}PaO_2/PAO_2$. Live E. coli infusion resulted in hypodynamic circulatory failure. Cardiac index fell from $3.7 \pm 0.8\ l \cdot min^{-1} \cdot m^{-2}$ to $2.2 \pm 0.7\ l \cdot min^{-1} \cdot m^{-2}$ after bacteremia lasting for 3.5 h. Simultaneously venous pulmonary vascular resistance rose from 25% of total pulmonary vascular resistance before to 32% after 3.5 h bacteremia, thus raising Pc from 11 mmHg to 16 mmHg. The degree of respiratory insufficiency was correlated with changes of MPP, dPa and dPv: $1\text{-}PaO_2/PAO_2 = 0.2 + 0.035 \cdot dPv$ ($r = 0.829$). Our results show, that the longitudinal distribution of pulmonary vascular resistance changes during septicemia, thus raising Pc. This may be an important factor in the genesis of septic pulmonary failure.

Key words: Septicemia – Pulmonary gas exchange – Pulmonary vascular resistance – Pulmonary veins – Pulmonary capillary pressure – ARDS – E. coli

Endotoxemia and bacteremia during septic shock may lead to pulmonary failure and pulmonary vasoconstriction [1–5]. Hemodynamic changes in the precapillary vascular system, caused by septicemia, are described in a number of investigations. Little is known, however, about the pulmonary venous vascular system. Kuida [6] was the first who, using isogravimetric methods, reported on pulmonary venoconstriction following E. coli endotoxinemia. Since Kuida's studies, however, the problem of pulmonary venoconstriction in septicemia has received little attention, until Holloway [7] recently described a simple method to calculate effective pulmonary capillary pressure (Pc) in intact organisms. Changes in pulmonary capillary pressure are easily determined using the method mentioned above [8–13]. The aim of our study was to investigate the effect of E. coli bacteremia on effective pulmonary capillary pressure, longitudinal distribution of pulmonary vascular resistance, and pulmonary function.

Materials and methods

The investigation was carried out on 9 healthy Goettingen minipigs (mean body weight 20.2 ± 3.4 kg). The animals were anesthetized with methohexital ($3\ mg \cdot kg^{-1} \cdot h^{-1}$), piritramide ($0.3\ mg \cdot kg^{-1} \cdot h^{-1}$) and relaxed with pancuronium bromide ($0.2\ mg \cdot kg^{-1} \cdot h^{-1}$). Artificial ventilation was carried out in ambient air at constant volume (Engström ER 311; tidal volume 13 ml/kg). The end expiratory CO_2-content was monitored continuously (Datex Normocap; 4.0–5.5 Vol% CO_2). The FiO_2 was raised when PaO_2 fell below 70 mmHg.

Hemodynamic parameters were obtained by means of a flowdirected 7F thermodilution catheter in the pulmonary artery, an arterial catheter positioned in the abdominal aorta, and a 3F catheter placed into the left atrium after minithoracotomy. All animals received $9 \pm 2\ ml \cdot kg^{-1} \cdot h^{-1}$ of an electrolyte solution containing glucose.

After a resting phase of 30 min and after raising the left atrial pressure (LAP) to 8 mmHg with hydroxyethyl starch weight averaged (molecular weight, 450000; 6% solution), the initial values were determined. Subsequently, $6.6 \pm 1.8 \cdot 10^6 \cdot kg^{-1}$ live E. coli in 50 ml nutrient solution supernatant were infused into a central vein at a rate of $12\ ml \cdot h^{-1}$. Two animals receiving no bacterial infusion served as control group.

The following parameters were measured at intervals of 30 min: heart rate (HR), central venous pressure (CVP), left atrial pressure (LAP), mean arterial pressure (MAP), mean pulmonary artery pressure (MPP), and cardiac output.

Blood samples were taken for arterial and mixed venous blood gas analysis. Alveolar PO_2 (PAO_2) was determined using a Beckmann Oxygen Analyzer OM11. Changing air pressure (P_{BARO}) was registered with the help of a precision barometer. PAO_2 was calculated as $PAO_2 = FiO_2\ (P_{BARO}\text{-}47\ mmHg)\text{-}PaCO_2/0.8$. The disturbance of pulmonary gas exchange was then quantified by the $AaDO_2$ quotient $1\text{-}PaO_2/PAO_2$ [14]. Cardiac output and vascular resistances were related to body surface.

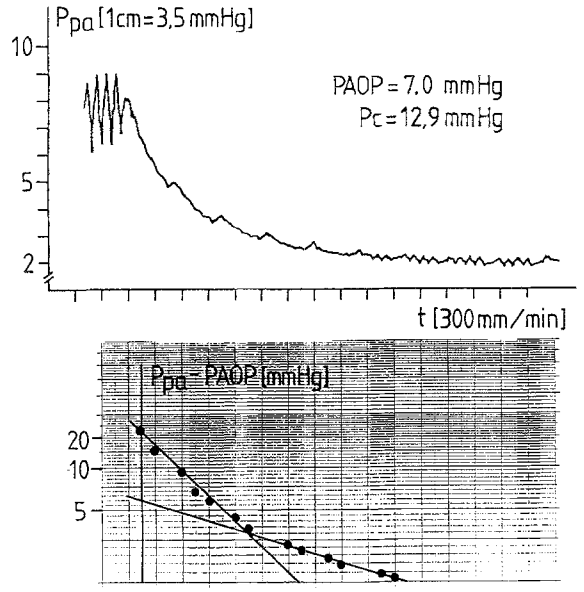

Fig. 1. *Above*: Pressure tracing following sudden occlusion of the pulmonary artery during bacteremia. The wedge pressure curve was registered at a paper speed of 300 mm/min. *Below*: Graphical analysis of the wedge pressure curve on semilogarithmic paper. Differences between several points on the wedge pressure curve and the pulmonary artery occlusion pressure are plotted as a function of time, which reveals two linear components. Extrapolation of the slow linear component back to the time of arterial occlusion leads to the pressure difference Pc-PAOP

Pulmonary capillary pressure was determined graphically as described by Holloway [7] and Cope [10]. The pulmonary arterial pressure curve was registered continuously by a recorder. The wedge pressure curve was plotted at a recording speed of 300 or 600 mm/min. Differences between single points on the actually registered pressure curve and the pulmonary artery occlusion pressure were then plotted on semi-logarithmic paper as a function of time. Thus, two different components of the pressure decay curve could be distinguished: a rapid and a slow linear component. The slow linear component was extrapolated back to the time of arterial occlusion, leading to a pressure intercept, which represents the pressure difference between Pc and PAOP (Fig. 1). This graphical determination of Pc corresponds to a pressure curve analysis on the base of a bi-exponential model [10, 15]. The precapillary pressure gradient (dPa) was then calculated as dPa = MPP-Pc, the postcapillary pressure gradient (dPv) as dPv = Pc-LAP. Airway pressure transmission on pulmonary artery pressure (dPAP) and pulmonary artery occlusion pressure (dPAOP) was determined in order to check the correct positioning of the thermodilution catheter and to recognize non-zone-III conditions. According to Teboul's recommendation, non-zone-III conditions were assumed when the quotient of airway pressure transmission on pulmonary artery occlusion pressure and pulmonary arterial pressure exceeded 1.5 (dPAOP/dPAP > 1.5) [16].

Statistical significance was checked using ANOVA for paired data; $p < 0.05$ was considered significant. The data of two animals which died during bacteremia were excluded from statistical analysis. Regression analysis was performed using the least square fitting method. Statistical significance of the regression was checked with F test.

Results

Infusion of live E. coli resulted in hypodynamic circulatory failure with marked pulmonary hypertension and acute respiratory insufficiency. The $AaDO_2$ quotient increased significantly from 0.27 before bacteremia to 0.52 and 0.61 after 2 h and 3.5 h E. coli infusion, respectively (Tables 1, 2). Peripheral vasoconstriction and rising systemic vascular resistance were able prevent a marked fall of arterial pressure (Table 1). After a 1 h E. coli infusion, CVP rose above initial readings, falling gradually during the remainder of the experiment (Table 1). Hypodynamic circulatory failure resulted in a significant decrease of cardiac index after 1 and 3.5 h E. coli bacteremia (Table 1). Oxygen delivery was thereby reduced, whereas oxygen consumption increased during bacteremia. Consequently mixed venous oxyen saturation decreased after 1 h bacteremia and was significantly reduced after 3.5 h E. coli infusion. In addition, bacteremia caused a marked hemoconcentration, as shown by a rise of hematocrit (Table 2).

Table 1. Hemodynamic data before (C), after 1 h (1), after 2 h (2) and after 3.5 h (3.5) of E. coli bacteremia

	C	1	2	3.5
HR (l/min)	96 ±26	99[29	107 ±20	115 ±36
CI (l/min·m^2)	3.7±0.8	2.3±0.6**	2.8±0.6**	2.2±0.7**
CVP (mmHg)	5 ±3	6 ±3	5 ±3	4 ±2
LAP (mmHg)	8 ±2	7 ±3 ns	7 ±3 ns	5 ±2 ns
MAP (mmHg)	94 ±17	78 ±28	91 ±26	84 ±31
MPP (mmHg)	20 ±2	36 ±6**	35 ±3**	39 ±6**
SVRI (dyn·s/cm^5·m^2)	2125 ±679	2969 ±1257	2721 ±740	3104 ±1281
PVRI (dyn·s/cm^5·m^2)	260 ±58	1206 ±434*	1024 ±599	1359 ±588*
RVSWI (g·m/m^2)	11 ±3.6	12 ±4.8	12 ±4.9	11 ±4.9
Pc (mmHg)	11 ±3	14 ±3 ns	15 ±5 ns	16 ±4 ns
dPa (mmHg)	8 ±2	22 ±5**	20 ±4**	23 ±3**
dPv (mmHg)	3 ±2	8 ±3 ns	8 ±2 ns	11 ±3**
dPAOP/dPAP	1.1±0.2	1.0±0.3	0.9±0.3	0.5±0.2

Heart rate (HR), cardiac index (CI), central venous pressure (CVP), left atrial pressure (LAP), mean arterial pressure (MAP), mean pulmonary artery pressure (MPP), systemic vascular resistance index (SVRI), pulmonary vascular resistance index (PVRI), right ventricular stroke work index (RVSWI), effective pulmonary capillary pressure (Pc), precapillary pressure gradient (dPa = MPP-Pc), postcapillary pressure gradient (dPv = Pc-LAP), quotient of airway-pressure transmission on pulmonary artery occlusion pressure (dPAOP) and pulmonary arterial pressure (dPAP) dPAOP/dPAP.

Mean values and standard deviation: see text for clarification.

*$p < 0.05$, **$p < 0.01$, ns not significant, compared with C

Table 2. Blood gas analysis and pulmonary function parameters before (C), after 1 h (1), after 2 h (2) and after 3.5 h (3.5) of E. coli bacteremia

	C	1	2	3.5
pH_a	7.46 ± 0.04	7.39 ± 0.06	7.40 ± 0.06	7.37 ± 0.07
P_aCO_2 (mmHg)	33 ± 4	35 ± 4	35 ± 3	34 ± 2
P_aO_2 (mmHg)	99 ± 17	115 ± 70	119 ± 52	92 ± 25
S_vO_2 (%)	70 ± 3	53 ± 13	61 ± 16	49 ± 9*
$1\text{-}P_aO_2/P_AO_2$	0.27 ± 0.06	0.49 ± 0.10	0.52 ± 0.06**	0.61 ± 0.14**
Hct (%)	25 ± 4	28 ± 4 ns	31 ± 4 ns	35 ± 6 ns
DO_2 (ml/min·m²)	380 ± 95	283 ± 59 ns	358 ± 138 ns	269 ± 117 ns
VO_2 (ml/min·m²)	101 ± 20	117 ± 31	119 ± 30	141 ± 38

pH_a, $PaCO_2$, PaO_2, mixed venous oxygen saturation (S_vO_2), $AaDO_2$ quotient $1\text{-}PaO_2/PAO_2$, hematocrit (Hct), oxygen delivery (DO_2 and oxygen consumption (VO_2).
Mean values and standard deviation: see text for clarification.
*$p<0.05$, **$p<0.01$, ns not significant, compared with C

After 1 h E. coli bacteremia mean pulmonary artery pressure rose significantly, remaining at this elevated level during the whole observation period. The marked increase of MPP caused a significant rise of precapillary pressure gradient during the experiment (Table 1). Pulmonary capillary pressure tended to increase during E. coli infusion and rose from mean 11 mmHg before bacteremia to mean 16 mmHg after 3.5 h, whereas LAP tended to fall. The postcapillary pressure gradient, therefore, increased significantly (Table 1). Venous pulmonary vascular resistance accounted for 25% of total pulmonary vascular resistance (PVR) before bacteremia and for 32% of PVR after 3.5 h bacteremia. The change of the longitudinal distribution of PVR made the Pc rise (Fig. 2).

During bacteremia pulmonary venous admixture rose above 15% in 7 animals, whereas the other two animals did not exceed 6.8% and 5.5%, respectively. The group with marked pulmonary dysfunction had a maximum AaDO2 quotient of mean 0.67, exceeding the values of animals with minor pulmonary disorder, which had AaDO2 quotients of 0.51 and 0.53, respectively. In animals showing considerable pulmonary disorders during bacteremia cardiac index fell to a mean of 88% the initial value, whereas in animals developing only minor pulmonary dysfunction cardiac index dropped to 62% and 72%, respectively.

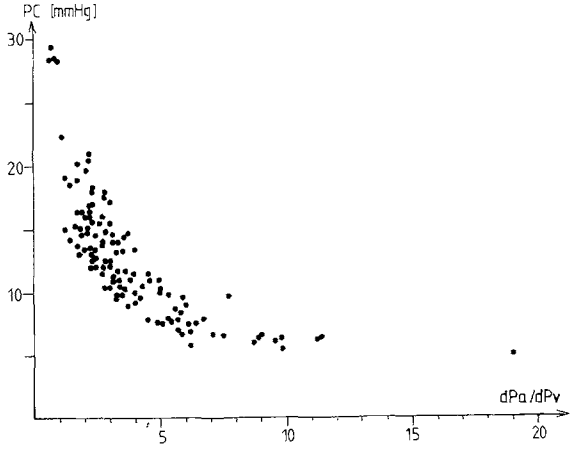

Fig. 2. Pulmonary capillary pressure (*Pc*) is determined by the ratio between precapillary and postcapillary pressure gradients (dPa/dPv)

Initial, highest, and second highest readings of dPv during bacteremia correlated well with the $AaDO_2$ quotient, provided the stroke volume index exceeded 15 ml·m^{-2} ($1\text{-}PaO_2/PAO_2 = 0.2+0.0035\cdot dPv$; $r = 0.829$; $n = 23$; $p<0.001$; Fig. 3). In addition we found significant corellations between $AaDO_2$ quotient and MPP ($1\text{-}PaO_2/PAO_2 = -0.04+0.016\cdot MPP$; $r = 0.808$; $n = 23$; $p<0.001$), dPa ($1\text{-}PaO_2 = 0.16+0.018\cdot dPa$; $r = 0.703$; $n = 23$; $p<0.001$; Fig. 4) and to a lesser degree between $AaDO_2$ quotient and Pc ($1\text{-}PaO_2/PAO_2 = 0.11 + 0.024\cdot Pc$; $r = 0.554$; $n = 23$; $p<0.01$; Fig. 5).

Two animals died during the experiment, one after 2 h and 10 min, the other after 2 h and 30 min. Both animals were able to maintain good circulatory conditions at the beginning of bacteremia, thus developing considerable pulmonary deterioration. Finally, however, these animals died due to circulatory insufficiency.

The relation of airway pressure transmission on wedge pressure and pulmonary arterial pressure did not increase during bacteremia. dPAOP/dPAP remained below 1.5, which allows the assumption that zone-III conditions were given in all Pc-measurements.

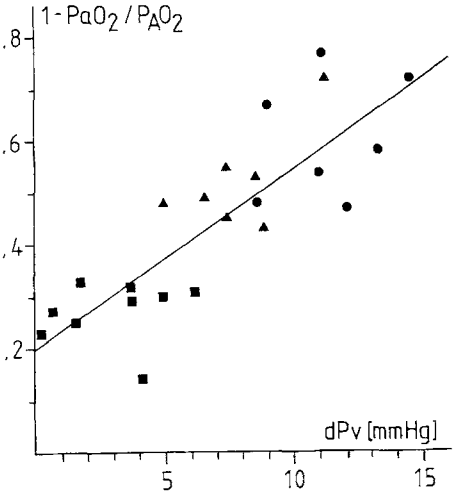

Fig. 3. Correlation between pulmonary venous pressure gradient dPv (*dPv* = Pc-LAP) and $AaDO_2$ quotient $1\text{-}PaO_2/PAO_2$. Before bacteremia (■), highest dPv values (●), and second highest dPv values (▲) during bacteremia (stroke volume index >15 ml·m^{-2}) $1\text{-}PaO_2/PAO_2 = 0.2+0.035\cdot dPv$; $r = 0.829$; $n = 23$; $p<0.001$

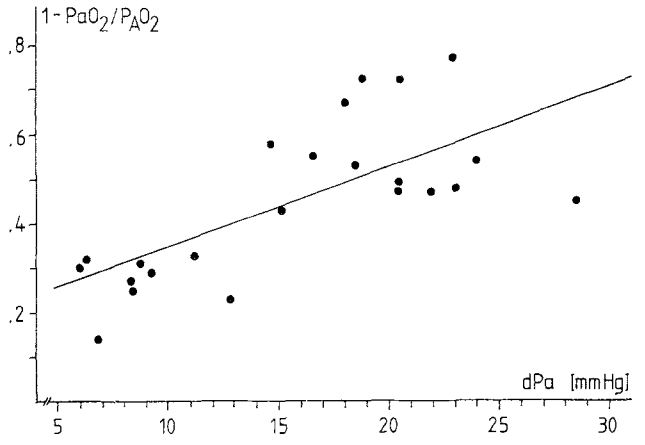

Fig. 4. Correlation between precapillary pressure gradient dPa (dPa = MPP-Pc) and $AaDO_2$ quotient $1\text{-}PaO_2/PAO_2$ (Same time points as Fig. 3.) $1\text{-}PaO_2/PAO_2 = 0.16 + 0.018 \cdot dPa$; $r = 0.703$; $n = 23$; $p < 0.001$

In all animals autopsy was performed after E. coli bacteremia, revealing a substantial dilation of the right ventricle and occasionally subendocardial hemorrhage. The pericardium was always intact showing especially no signs of pericardial hematoma or cardiac tamponade.

No notable changes were found in hemodynamic data or pulmonary gas exchange of the 2 animals serving as control group during a 4 h observation period. Post mortem examination of these animals also did not reveal any pathological findings.

Discussion

In 1983 Holloway described a method to determine effective pulmonary capillary pressure in intact organisms from a wedge pressure profile [7]. With its help it became possible to determine the longitudinal distribution of pulmonary vascular resistance under varying conditions. Any interpretation of data obtained by the above mentioned method, however, has to be in context of its methodical limits. Experiments on isolated perfused lung lobes with pulmonary arterial and venous occlusion supplied a simple hemodynamic lung model, which is usefull for the interpretation of pulmonary arterial wedge pressure curves [17]. This hemodynamic model of the lung consists of three serial resistances, a precapillary upstream resistance, a postcapillary downstream resistance and a middle resistance. The latter is closely related to maximum vascular compliance and corresponds to the capillary vascular system. When Pc is determined using the arterial occlusion method, the result corresponds to the pressure at the upstream end of the middle resistance. Thus, Pc overestimates the average pressure of the middle compartment, which leads to a minor error, when the middle compartment's resistance is low. An increase of the middle resistance, however, may lead to falsely high Pc values [15].

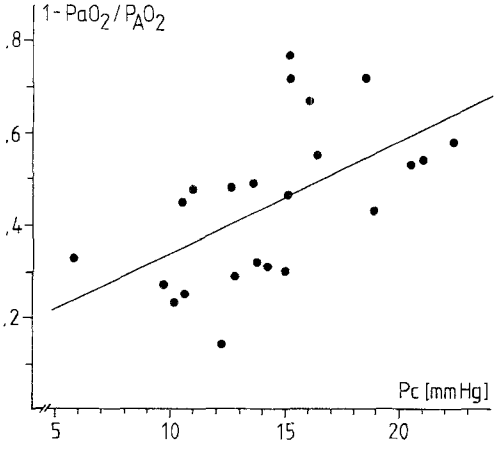

Fig. 5. Correlation between effective pulmonary capillary pressure (Pc) and $AaDO_2$ quotient $1\text{-}PaO_2/PAO_2$ (Same time points as Fig. 3.) $1\text{-}PaO_2/PAO_2 = 0.11 + 0.024 \cdot Pc$; $r = 0.554$; $n = 23$; $p < 0.01$

Hakim [17], looking for changes of the middle compartment's resistance, localized a mere 16% of pulmonary vascular resistance in the middle compartment and failed to observe any changes of the middle compartment's pressure gradient during precapillary vasoconstriction caused by serotonin or postcapillary vasoconstriction caused by histamine infusion. Even a 7–10 fold increase of pulmonary blood flow, designed to alter the middle compartment's resistance, did not lead to apparent differences between Pc determined by arterial occlusion and effective filtration pressure determined by isofiltration techniques [18]. Correspondingly Dawson [15] found no tendency to overestimate the effective filtration pressure when Pc was determined from the pressure decay after rapid arterial occlusion, even during pre- or postcapillary vasoconstriction. On the contrary he observed a good correlation between Pc and the effective filtration pressure determined by simultaneous arterial and venous occlusion.

While the previous studies [15, 17–19] indicate, that drug induced changes of the longitudinal distribution of pulmonary vascular resistance have only little effect on the middle resistance, these changes nevertheless constitute an unavoidable source of error in Pc determination. A further source of error when analyzing wedge pressure curves, is the point of time during the cardiac cycle at which pulmonary arterial occlusion occurs [20]. The intravascular pulmonary volume changes with the different phases of the cardiac cycle, which might influence the pressure decay after pulmonary arterial occlusion. Pc values, will therefore differ according to the point of time at which pulmonary arterial occlusion occurs. In addition, poor pressure transmission due to the length of the pulmonary artery catheter and artefacts during inflation of the balloon may lead to an increased variability of Pc data. Despite these imponderables Pc determination from wedge pressure curves is a valuable method being accepted critically by an increasing number of clinical investigators [11, 15, 21].

E. coli bacteremia and endotoxinemia have been used in a number of experiments to imitate acute pulmonary failure [1, 2, 6, 8, 9]. Correspondingly in our experiment E. coli bacteremia led to hypodynamic circulatory failure and acute respiratory insufficiency. Circulatory failure

was mainly caused by an acute increase of right ventricular afterload and consecutive right ventricular insufficiency. Massive pulmonary hypertension during bacteremia, right ventricular dilation observed at post mortem examination and the inability of the animals to increase their right ventricular stroke work during bacteremia support our point of view. In part, right ventricular insufficiency may be related to relative hypovolemia. During our investigation we observed pathophysiologic changes without therapeutical interferences. Consequently the animals received no volume resuscitation during bacteremia, which led to a decrease of LAP. The tendency of CVP to rise after 1 h bacteremia, therefore, would not be a sign of normovolemia but of the right ventricle's attempt to compensate for pulmonary hypertension. Impairment of left ventricular function caused by right ventricular dilation and ventricular interdependence seems likely. Therefore peripheral vasoconstriction has to be interpreted as an attempt to maintain normal perfusion pressure at reduced flow rates. Reduced systemic blood flow decreased oxygen supply and caused a significant decrease of mixed venous oxygen saturation after 3.5 h bacteremia, thus indicating insufficient periphereal oxygenation.

As observed earlier by Borg [1], impairment of pulmonary function was most pronounced in animals with well preserved circulatory function, whereas animals with marked circulatory failure revealed only little impairment of gas exchange. In Borg's spontaneously breathing animals and in our experiment, where PEEP was not applied during mechanical ventilation, functional residual capacity of the lung may have dropped considerably during bacteremia, causing regional hypoventilation and atelectasis. Animals with normal or relatively high cardiac output therefore revealed high intrapulmonary shunt values, whereas animals with low cardiac output showed only minor pulmonary deterioration [1]. Mortality during E. coli endotoxinemia, however, was not related to the degree of pulmonary shunting, but significantly related to the degree of pulmonary vasoconstriction [1], which indicates, that the increase in pulmonary vascular resistance is the major pathophysiologic factor in acute respiratory failure [3, 22].

Data on the longitudinal distribution of total pulmonary vascular resistance vary greatly in the literature [6–13, 23], dPv accounting for 22–44% of total pulmonary vascular resistance, respectively. The wide variety may be due to the different methods applied in determining Pc and/or to physiological differences of the various species used in the experiments. In our investigation, 25% of pulmonary vascular resistance is located in the postcapillary vascular bed. These data match well with D'Orio's [8] and Cope's [10] results, who found 22% and 34% of the pulmonary vascular resistance located in the postcapillary vascular system.

The simultaneous decrease of cardiac index and increase of dPv during bacteremia indicates elevated postcapillary pulmonary vascular resistance caused by either active venoconstriction [6, 8] and/or by passive venocompression due to perivascular edema. As effective pulmonary capillary pressure is determined by the ratio between pre- and postcapillary resistance, the increase in postcapillary pulmonary vascular resistance causes a rise of Pc (Fig. 2), which again enhances transvascular fluid filtration [7, 21]. According to Grimbert [21], during acute lung injury the transvascular fluid filtration rate is multiplied eightfold, if pulmonary capillary pressure increases by only 3 mmHg. The increase of hematocrit observed during bacteremia indicates a loss of intravascular fluid, which in the lungs most likely led to interstitial pulmonary edema. This in turn reduces the compliance of the interstitial space, thereby worsening alveolar ventilation [24]. An increase of extravascular lung water, therefore, may contribute to ventilation perfusion disturbances which are suspected to be the major cause of acute respiratory failure in human sepsis [25] and during E. coli endotoxinemia [1]. Thus, changes in the longitudinal distribution of pulmonary vascular resistance which raise pulmonary capillary pressure may play a role at least in the early phase of septic pulmonary disorders.

References

1. Borg T, Alvfors A, Gerdin B, Modig J (1985) A porcine model of early adult respiratory distress syndrome induced by endotoxinaemia. Acta Anaesth Scand 29:814–830
2. Brigham KL, Bowers RE, Haynes J (1979) Increased sheep lung vascular permeability caused by Escherichia coli endotoxin. Circ Res 45:292–297
3. Klöss T, Birkenhauer U, Kottler B (1989) Pulmonary pressure-flow relationshhip and peripheral oxygen supply in ARDS due to bacterial sepsis. In: Schlag G, Redl H (eds) 2nd Vienna Shock Forum. Liss, New York, pp 175–180
4. Reeves JT, Daoud FS, Estridge H (1972) Pulmonary hypertension caused by minute amounts of endotoxin in calves. J Appl Physiol 33:739–743
5. Sibbald WJ, Paterson NAM, Holliday RL, Anderson RA, Lobb TR, Duff JH (1978) Pulmonary hypertension in sepsis. Chest 73:583–591
6. Kuida H, Hinshaw LB, Gilbert RP, Visscher MB (1958) Effect of gram-negative endotoxin on pulmonary circulation. Am J Physiol 192:335–344
7. Holloway H, Perry M, Downey J, Parker J, Taylor A (1983) Estimation of effective pulmonary capillary pressure in intact lungs. J Appl Physiol 54:846–851
8. D'Orio V, Halleux J, Rodriguez LM, Wahlen C, Marcelle R (1986) Effects of Escherichia coli endotoxin on pulmonary vascular resistance in intact dogs. Crit Care Med 14:802–806
9. Baer ER, Pearl RG, Siegel LC, Rice SA (1988) Longitudinal distribution of pulmonary vascular resistance during endotoxin-induced pulmonary hypertension in sheep (Abstract). Anesthesiology 69:3A, A860
10. Cope DK, Allison RC, Parmentier JL, Miller JN, Taylor AE (1986) Measurement of effective pulmonary capillary pressure using the pressure profile after pulmonary artery occlusion. Crit Care Med 14:16–22
11. Collee GG, Lynch KE, Hill RD, Zapol WM (1987) Bedside measurement of pulmonary capillary pressure in patients with acute respiratory failure. Anesthesiology 66:614–620
12. Siegel LC, Pearl RG (1988) The longitudinal distribution of pulmonary vascular resistance during thrombin-induced microembolization in sheep (Abstract). Anesthesiology 69:3A, A857
13. Pearl RG, Siegel LC, Baer ER (1988) Vasodilators and the longitudinal distribution of pulmonary vascular resistance (Abstract). Anesthesiology 69:3A, A154
14. Benzer H, Haider W, Mutz N, Geyer A, Goldschmied W, Pauser G, Baum M (1979) Der alveolo-arterielle Sauerstoffquotient = "Quotient" = PAO2-PaO2/PAO2. Anaesthesist 28:533–539

15. Dawson CA, Bronikowski TA, Linehan JH, Haworth ST, Rickaby DA (1989) On the estimation of pulmonary capillary pressure from arterial occlusion. Am Rev Respir Dis 140:1228–1236
16. Teboul JL, Besbes M, Axler O, Rekik N, Brun-Buisson C, Lemaire F (1988) Relationship between pulmonary artery occlusive pressure (PAOP) and left ventricular end diastolic pressure: role of catheter tips location and of PEEP (Abstract). Intensive Care Med 14: [Suppl 1] 281
17. Hakim TS, Michel RP, Chang HK (1982) Partitioning of pulmonary vascular resistance in dogs by arterial and venous occlusion. J Appl Physiol 52:710–715
18. Bshouty Z, Ali J, Younes M (1987) Arterial occlusion versus isofiltration pulmonary capillary pressures during very high flow. J Appl Physiol 62:1174–1178
19. Yamada Y, Suzukawa M, Chinzei M, Suwa K, Numata K (1989) Pulmonary arterial, capillary and venous resistances from arterial occlusion (Abstract). Anesthesiology 71:3A, A172
20. Suzukawa M, Yamada Y, Chinzei M, Kawahara N, Chinzei T (1988) Phasic variation in pulmonary capillary pressure measured by time-controlled arterial occlusion (Abstract). Anesthesiology 69:3A, A217
21. Grimbert FA (1988) Effective pulmonary capillary pressure. Eur Respir J 1:297–301
22. Permutt S (1985) The role of pulmonary arterial pressure in experimentally induced acute lung injury. In: Zapol WM, Falke KJ (eds) Acute respiratory failure. Dekker, New York, pp 227–239
23. Gaar KA, Taylor AE, Owens LJ, Guyton AC (1967) Pulmonary capillary pressure and filtration coefficient in the isolated perfused lung. Am J Physiol 213:910–914
24. Borg T, Modig J (1985) Positive effects of prophylactic ventilator treatment on gas exchange and extravascular lung water in a porcine model of adult respiratory distress syndrome induced by endotoxinaemia. Acta Chir Scand 151:501–508
25. Siegel JH, Giovannini I, Coleman B (1979) Ventilation: perfusion maldistribution secondary to the hyperdynamic cardiovascular state as the major cause of increased pulmonary shunting in human sepsis. J Trauma 19:432–460

Dr. R. Fretschner
Klinik für Anaesthesiologie
und Transfusionsmedizin
der Universität Tübingen
Hoppe-Seyler-Straße 3
W-7400 Tübingen
Federal Republic of Germany