

Pulmonary mechanics and diffusion after 'shock lung'¹

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Yernault, J. C., Englert, M., Sergysels, R., and de Coster, A. (1975). Thorax, 30, 252–257. Pulmonary mechanics and diffusion after 'shock lung'. Pulmonary function studies performed in seven patients who had recovered from 'shock lung' showed a highly significant decrease of diffusing properties of the lung, a slight loss of lung recoil pressure, and a borderline increase of residual volume with normal vital capacity and total lung capacity. Pulmonary compliance was normal. The interpretation of these findings is discussed.

'Shock lung' (Proctor, Ballantine, and Broussard, 1970) is a syndrome of severe respiratory insufficiency accompanying shock of several aetiologies (trauma, hypovolaemia, haemorrhage, sepsis, etc.). The clinical evolution of the acute period can be roughly divided into four stages (Moore *et al.*, 1969; Gay and Campan, 1972; de Coster *et al.*, 1974):

1. Shock is treated by massive intravenous infusion. Hyperventilation with hypocapnia is sometimes present.
2. Moderate hypoxaemia appears some hours or days after haemodynamics have returned to normal; it resolves or progresses to stage 3.
3. Distress, tachypnoea, and cyanosis develop. Radiography shows mottled opacities which progressively opacify the entire lung. In spite of artificial ventilation with pure oxygen, arterial oxygen pressure remains low.
4. Severe hypoxaemia persists and eventually hypercapnia, loss of consciousness, and death.

The pathophysiology of this syndrome is still debated. Functional studies made during the acute period have shown a lowered pulmonary compliance (Henry *et al.*, 1967; Cahill *et al.*, 1965; Wilson *et al.*, 1969; Proctor *et al.*, 1970); diffusing properties of the lung have not been studied.

The aim of the present study was to evaluate the physiological sequelae in patients who had completely recovered from the acute syndrome.

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MATERIAL AND METHODS

Of 12 patients hospitalized in the medical intensive care unit of our hospital for shock lung syndrome from 1971 to 1973 eight have completely recovered. Seven of them have been studied after recovery one to 20 months after the acute period.

The clinical and therapeutic problems have been reported elsewhere (de Coster *et al.*, 1974) and are summarized in Table I. It should be emphasized that none of the patients had a history of previous pulmonary disease. At the time of the study physical examination and chest radiography were normal in all patients and all were symptom free except case 6, who complained of slight exertional dyspnoea.

The biometric characteristics of the subjects studied are reported in Table I, together with the time, in months, after the acute phase before the physiological studies were performed.

Vital capacity (VC) and one-second forced expiratory volume (FEV₁) were measured with a conventional spirometer. Functional residual capacity (FRC) was measured by the helium dilution method. Predicted values for lung volumes were calculated according to Grimby and Söderholm (1963), Berglund *et al.* (1963), and Birath, Kjellmer, and Sandqvist (1963).

Airway resistance (Raw) was determined by constant volume body plethysmography; the predicted values are those of Amrein *et al.* (1970).

Diffusing properties of the lung were studied by the carbon monoxide single-breath method; the

TABLE I
BIOMETRIC CHARACTERISTICS OF THE SUBJECTS STUDIED

Patient	Sex	Age (years)	Height (metres)	Weight (kg)	Aetiology of Shock	Duration of Artificial Ventilation (days)	Duration of Study after 'Shock Lung' (months)
1	F	35	1.67	60	Septic and hypovolaemic	13	20
2	F	42	1.50	42	Septic and hypovolaemic	40	3
3	F	30	1.60	52	Hypovolaemic with acute renal failure	2	1
4	F	29	1.68	48	Septic and hypovolaemic with renal failure	7	3
5	F	52	1.57	56	Septic with renal failure	3	11
6	F	22	1.64	49	Septic	9	3
7	M	38	1.71	65	Hypovolaemic and septic	16	3

normal values are those of Englert (1967). The transfer factor was calculated using both the effective alveolar volume measured using the dilution of helium during breath-holding (TF^1) and the alveolar volume measured by adding the inspired volume to the residual volume previously determined by the multiple-breath helium dilution method (TF).

Oesophageal pressure was measured with a Latex balloon (length 10 cm, perimeter 5 cm) containing 1 ml of air. With the balloon in the lower third of the oesophagus, the subject breathed into a bag containing air at 37°C and saturated with water vapour. After a few normal breaths, during which the end expiratory level and the zero pressure were carefully noted, the subject took a full inspiration, then expired slowly to or slightly under the FRC level; during the next very slow deep inspiratory and expiratory manoeuvres (to or near residual volume level), transpulmonary pressure and volume were directly recorded on an X-Y recorder. At least two correct measurements were obtained for each subject (i.e., measurements with total lung volume very close to previously determined total lung capacity (TLC) and without evident artefact of

pressure). From these tracings, static inspiratory (CLI) and expiratory (CLE) compliances were calculated from the transpulmonary pressure variation between FRC and FRC+0.5 litre. The normal values for compliance were determined in a group of 22 young adults (Yernault and Englert, 1974). Maximal inspiratory pressure (PI max) and elastic recoil at various levels of total lung capacity (Pst) were compared to the normal values established by Turner, Mead, and Wohl (1968). Finally, the coefficient of retraction (CR), according to Schlueter, Immekus, and Stead (1967), was calculated by dividing Pst at 100% TLC by TLC.

A previously described partially computerized program (Yernault *et al.*, 1972) was used for the calculations and presentation of results.

Pulmonary scanning was performed in three patients (cases 1, 2, and 3) with a gamma camera after intravenous injection of technetium-99m labelled microspheres.

RESULTS

Table II shows the results of measurements of lung volumes: vital capacity is slightly lowered, but functional residual capacity, measured either

TABLE II
PULMONARY VOLUME MEASUREMENTS

Patient	Vital Capacity (l.)	Functional Residual Capacity (l.)	Residual Volume (l.)	Total Lung Capacity (l.)	RV/TLC (%)	FEV ₁ (l.)	FEV ₁ /VC (%)
1	3.71(3.84)	3.59(2.42)	2.05(1.41)	5.76(5.26)	36(27)	3.05(3.19)	82(83)
2	2.35(2.95)	2.25(1.89)	1.35(0.94)	3.70(3.90)	37(24)	1.97(2.40)	84(81)
3	3.27(3.71)	2.97(2.19)	1.56(1.11)	4.83(4.82)	32(23)	3.17(3.14)	97(85)
4	3.36(4.03)	3.09(2.49)	1.73(1.38)	5.09(5.40)	34(25)	2.92(3.40)	87(85)
5	2.69(3.02)	3.43(2.08)	1.99(1.23)	4.68(4.25)	43(29)	2.21(2.37)	82(79)
6	3.57(4.02)	2.90(2.32)	1.34(1.16)	4.91(5.18)	27(22)	3.03(3.47)	85(86)
7	3.25(5.00)	3.23(3.47)	1.71(1.80)	4.96(6.81)	34(26)	2.30(3.90)	71(78)
Mean observed	3.17	3.07	1.68	4.85	34.7	2.66	84
SD	0.48	0.44	0.28	0.61	4.9	0.49	7.7
Mean predicted	3.80	2.41	1.29	5.09	25.2	3.12	82.4
SD	0.69	0.51	0.28	0.94	2.4	0.56	3.2
	NS	0.025	0.025	NS	0.001	NS	NS

Predicted values are shown in parentheses. The mean value of the group studied is compared to the mean predicted value. The significance of the difference between the two groups is also reported (NS = not significant).

by helium dilution or by body plethysmography, and residual volume (RV) are significantly increased; total lung capacity remains normal. The increase of the RV/TLC ratio is highly significant, but the ratio FEV₁/VC is normal.

In Table III are recorded the diffusing properties of the lung. When calculated by the classical method, TF is slightly greater than when calculated using effective alveolar volume, but whatever the method used there is a highly significant reduction of TF. The Krogh constant (k) is also significantly lowered.

The mechanical properties are presented in Table IV. Airways resistance is normal, as are both CLI and CLE. A moderate loss of lung recoil is apparent in five patients, as shown by a low PI max and low Pst at different lung volumes (Figure). It is of interest that the only subject with

normal lung recoil had been ventilated with a residual positive expiratory pressure of 30 mmHg.

Pulmonary scanning was normal in two patients (cases 1 and 3) and showed heterogeneity of perfusion in one (case 2).

DISCUSSION

The diagnosis of shock lung was firmly established in all the cases reported on clinical, radiological, and physiological bases. Aetiology was, however, not uniform and the severity of the disease varied, as could be judged from the varying duration of artificial ventilation needed (de Coster *et al.*, 1974).

Nevertheless the physiological findings are remarkably constant. Total lung capacity is normal but the ratio RV/TLC tends to be high; there is no sign of airway obstruction, airway resistance and the FEV₁/VC ratio being normal in all cases, compliance is normal but there is a slight loss of lung recoil in most patients; transfer factor is strikingly reduced. Interpretation of the increase in FRC, RV, and RV/TLC must be cautious, since in absolute values it is only slight and depends on the normal values used. For example, if RV is predicted according to Needham, Rogan, and McDonald (1954) or to Goldman and Becklake (1959), there is no significant variation from normal. Previous reports from our laboratory have drawn attention to these problems (de Coster and Schmitz-Cusnier, 1970; de Coster, Messin and Degré, 1967), but recent studies (Yernault and Englert, 1974) seem to confirm the validity of the reference values which are used in the present work.

TABLE III
MEASUREMENTS OF DIFFUSING PROPERTIES

Patient	Transfer Factor (ml min ⁻¹ mmHg ⁻¹) ¹ TF ¹		Krogh's Constant min ⁻¹ k
1	17.3(26.7)	19.9	3.22(4.63)
2	10.7(18.5)	11.5	2.81(4.42)
3	10 (25.6)	10.5	2.08(4.84)
4	12.8(25.4)	13.6	2.77(4.81)
5	12.1(20.3)	13.7	2.69(4.12)
6	18.5(26.8)	18.4	3.41(5.02)
7	7.1(27.6)	—	1.55(4.37)
Mean observed	12.6	14.6	2.65
SD	4	3.8	0.64
Mean predicted	24.4	23.9	4.6
SD	3.5	3.6	0.31
	0.001	0.005	0.001

¹To convert to SI units (mmol min⁻¹ kPa⁻¹) multiply by 0.335. Predicted values are shown in parentheses. The mean value of the group studied is compared to the mean predicted value. The significance of the difference between the two groups is also reported.

TABLE IV
MEASUREMENTS OF MECHANICAL LUNG PROPERTIES

Patient	Airways Resistance (cmH ₂ O l ⁻¹ sec ⁻¹) ¹	Inspiratory Quasi-static Compliance (l cmH ₂ O ⁻¹) ²	Expiratory Quasi-static Compliance (l cmH ₂ O ⁻¹) ²	Transpulmonary Pressure at Full Inspiration (cm H ₂ O) ¹	Coefficient of Retraction (cmH ₂ O l ⁻¹) ¹
1	2.4 (1.8)	0.185 (0.177)	0.160 (0.240)	27.1 (33.9)	4.8 (6.4)
2	1.5 (1.8)	0.133 (0.094)	0.174 (0.125)	18.5 (30.9)	4.5 (7.9)
3	2.1 (1.8)	0.153 (0.143)	0.200 (0.193)	27.8 (34.3)	5.3 (7.1)
4	1.8 (1.8)	0.136 (0.182)	0.141 (0.247)	24.5 (34.3)	5.1 (6.4)
5	1.4 (1.8)	0.181 (0.128)	0.190 (0.172)	21.7 (26.7)	4.4 (6.3)
6	2.5 (1.8)	0.148 (0.162)	0.181 (0.220)	35.2 (34.3)	5.9 (5.2)
7	—	—	0.215 (0.267)	30.1 (32.7)	6.0 (4.8)
Mean observed	1.95	0.156	0.180	26.4	5.1
SD	0.46	0.022	0.025	5.5	0.6
Mean predicted	1.8	0.148	0.209	32.4	6.3
SD	0	0.033	0.049	2.8	1.1
	NS	NS	NS	0.025	NS

To convert to SI units:

¹Multiply by 0.1 (kPa per cm H₂O).

²Multiply by 10 (kPa per cm H₂O).

Predicted values are shown in parentheses. The mean value of the group studied is compared to the mean predicted value. The significance of the difference between the two groups is also reported (NS = not significant).

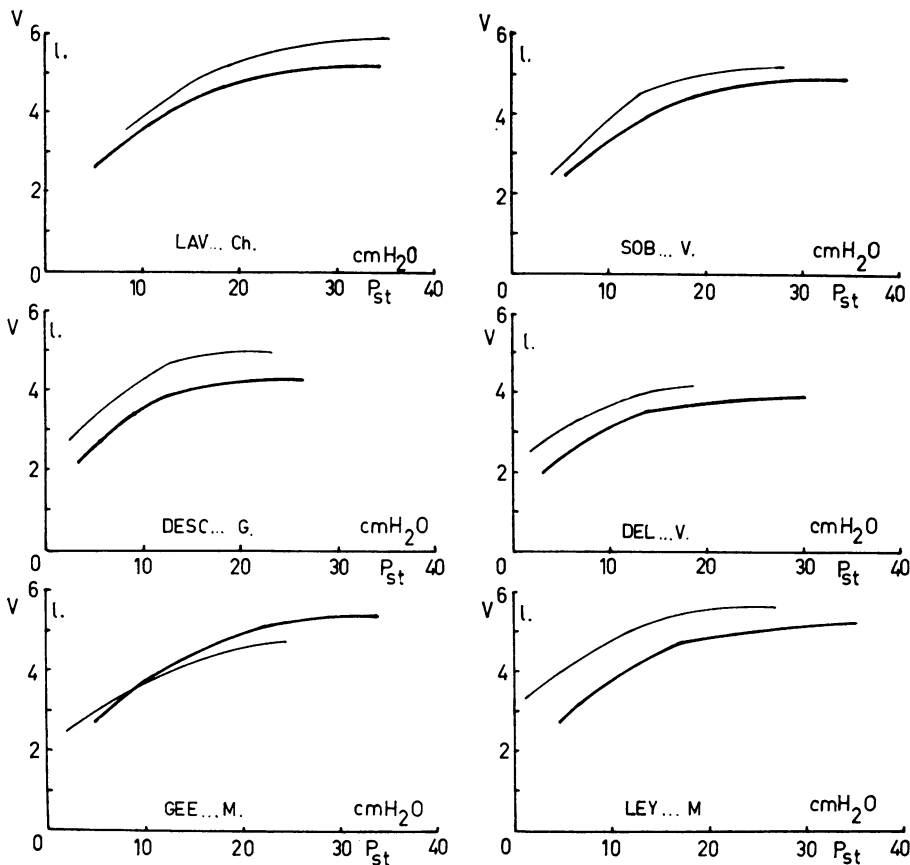


FIGURE Representation of volume-pressure curves of the subjects studied. The thick line is the predicted curve, the thin line the measured one.

These borderline abnormalities in FRC, RV, and RV/TLC could be related to the loss of lung recoil. It is not, however, of sufficient degree to suggest pulmonary emphysema, although in patients who died from 'solid lung', Wyatt (1973) described overexpansion of air ducts and air sacs in the unconsolidated areas. The most likely explanation seems a modification in lung surface properties: such modifications have indeed been induced experimentally by tracheal obstruction in dogs *in vivo* (Buhain, Brody, and Fisher, 1972) or by ventilation of excised dog lungs with an end expiratory pressure of 7 cmH₂O (Raimondi, Massarella, and Pride, 1971).

The important reduction of transfer factor of the lung is the most characteristic feature in all patients. Few studies have as yet been performed in this field. Interiano, Stuard, and Hyde (1972)

showed a reduction of the diffusing capacity of the lung in one patient, studied after acute respiratory distress following acute pancreatitis. Downs and Olsen (1974) also reported a transient reduction of TF in one patient after adult respiratory distress syndrome. In the present series also the lowest values of TF are seen soon after the acute phase.

The reduction of diffusing capacity of the lung is probably related to disturbances at the capillary level. Extensive pulmonary arterial thrombosis can be excluded by the studies of the distribution of pulmonary perfusion performed in three cases, but diffuse thrombosis or destruction of the capillaries are known to occur during the acute phase of the disease (Hardaway *et al.*, 1967; Dalldorf *et al.*, 1968; Martin, Soloway, and Simmons, 1968; Groves *et al.*, 1972; Pariente *et*

al., 1972). From the present results it appears that these disturbances are, at least partly, irreversible.

It should be emphasized that these disturbances of diffusing properties of the lung are present without any sign of pulmonary fibrosis, which is known to develop in fatal cases (Hardaway *et al.*, 1967; Wilson *et al.*, 1969; Bredenberg *et al.*, 1969): pulmonary compliance and total lung capacity are indeed perfectly normal in all seven cases.

Although definite, the reported changes of lung function seem not to be of major clinical significance since Pao_2 at rest was normal in each patient before discharge from hospital. The long-term evolution is, however, impossible to predict and needs further studies.

REFERENCES

- Amrein, R., Keller, R., Joos, H., and Herzog, H. (1970). Valeurs normales de l'exploration de la fonction pulmonaire par la pléthysmographie corporelle. *Journal Français de Médecine et Chirurgie Thoraciques*, **24**, 245.
- Berglund, E., Birath, G., Bjure, J., Grimby, G., Kjellmer, I., Sandqvist, L., and Söderholm, B. (1963). Spirometric studies in normal subjects. Forced expirograms in subjects between 7 and 70 years of age. *Acta Medica Scandinavica*, **173**, 185.
- Birath, G., Kjellmer, I., and Sandqvist, L. (1963). Spirometric studies in normal subjects. Ventilatory capacity tests in adults. *Acta Medica Scandinavica*, **173**, 193.
- Bredenberg, C. E., James, P. M., Collins, J., Anderson, R. W., Martin, A. M., and Hardaway, R. M. (1969). Respiratory failure in shock. *Annals of Surgery*, **169**, 392.
- Buhain, W. J., Brody, J. S., and Fisher, A. B. (1972). Effect of artificial airway obstruction on elastic properties of the lung. *Journal of Applied Physiology*, **33**, 589.
- Cahill, J. M., Jouasset-Strieder, D., and Byrne, J. J. (1965). Lung function in shock. *American Journal of Surgery*, **110**, 324.
- Dalldorf, F. G., Carney, C. N., Rackley, C. E., and Raney, R. B. (1968). Pulmonary capillary thrombosis in septicemia due to Gram-positive bacteria. *Journal of the American Medical Association*, **206**, 583.
- de Coster, A., Messin, R., and Degré, S. (1967). Interprétation des résultats spirographiques. *Acta Tuberculosa et Pneumologica Belgica*, **58**, 557.
- and Schmitz-Cusnier, C. (1970). Les volumes pulmonaires de la femme: variations physiologiques. In *Normal Values for Respiratory Function in Man*, edited by P. Arcangeli, J. E. Cotes, A. Cournand, H. Denolin, G. Di Maria, P. Sadoul, M. Scherrer, and G. L. Scarpa, pp. 154–169. Panminerva Medica, Rome.
- , Sergysels, R., Degaute, J. P., Jaspar, N., and Englert, M. (1974). Le concept du poumon de choc. *Lille Médical*, **19**, 424.
- Downs, J. B. and Olsen, G. N. (1974). Pulmonary function following adult respiratory distress syndrome. *Chest*, **65**, 92.
- Englert, M. (1967). *Le Réseau Capillaire Pulmonaire chez l'Homme*. Masson, Paris.
- Gay, R. and Campan, L. (1972). Manifestations pulmonaires des états de choc: poumon de choc? *Bulletin de Physio-pathologie Respiratoire*, **8**, 731.
- Goldman, H. I. and Becklake, M. R. (1959). Respiratory function tests. Normal values at median altitudes and the prediction of normal results. *American Review of Respiratory Diseases*, **79**, 457.
- Grimby, G. and Söderholm, B. (1963). Spirometric studies in normal subjects: static lung volumes and maximum voluntary ventilation in adults with a note on physical fitness. *Acta Medica Scandinavica*, **173**, 199.
- Groves, A. C., Griffiths, J., Leung, F. Y. T., and Naiman, S. C. (1972). Fibrin thrombi in the pulmonary microcirculation of dogs with Gram-negative bacteremia. *Surgery, Gynecology and Obstetrics*, **134**, 433.
- Hardaway, R. M., James, P. M., Anderson, R. W., Bredenberg, C. E., and West, R. L. (1967). Intensive study and treatment of shock in man. *Journal of the American Medical Association*, **199**, 779.
- Henry, J. N., McArdle, A. H., Scott, H. J., and Gurd, F. N. (1967). A study of the acute and chronic respiratory pathophysiology of hemorrhagic shock. *Journal of Thoracic and Cardiovascular Surgery*, **54**, 666.
- Interiano, B., Stuard, I. D., and Hyde, R. W. (1972). Acute respiratory distress syndrome in pancreatitis. *Annals of Internal Medicine*, **77**, 923.
- Martin, A. M., Soloway, H. B., and Simmons, R. L. (1968). Pathologic anatomy of the lungs following shock and trauma. *Journal of Trauma*, **8**, 687.
- Moore, F. D., Lyons, J. H., Pierce, E. C., Morgan, A. P., Drinker, P. A., MacArthur, J. D., and Dammin, G. J. (1969). *Posttraumatic Pulmonary Insufficiency*. Saunders, Philadelphia.
- Needham, C. D., Rogan, M. C., and McDonald, R. (1954). Normal standards for lung volumes, intrapulmonary gas-mixing, and maximum breathing capacity. *Thorax*, **9**, 313.
- Pariente, R., André, J., Legrand, M., and Brouet, C. (1972). Les lésions élémentaires ultrastructurales du poumon. *Nouvelle Presse Médicale*, **1**, 1351.
- Proctor, H. J., Ballantine, T. V. N., and Broussard, N. D. (1970). An analysis of pulmonary function following non-thoracic trauma, with recommendations for therapy. *Annals of Surgery*, **171**, 180.
- Raimondi, A. C., Massarella, G. R., and Pride, N. B. (1971). The effects of ventilation on the elastic

- recoil of excised dogs' lungs. *Respiration Physiology*, **12**, 205.
- Schlueter, D. P., Immekus, J., and Stead, W. W. (1967). Relationship between maximal inspiratory pressure and total lung capacity (coefficient of retraction) in normal subjects and patients with emphysema, asthma, and diffuse pulmonary infiltration. *American Review of Respiratory Diseases*, **96**, 656.
- Turner, J. M., Mead, J., and Wohl, M. E. (1968). Elasticity of human lungs in relation to age. *Journal of Applied Physiology*, **25**, 664.
- Wilson, R. F., Kafi, A., Asuncion, Z., and Walt, A. J. (1969). Clinical respiratory failure after shock or trauma. *Archives of Surgery*, **98**, 539.
- Wyatt, J. P. (1973). Lung patterns in emphysema. *Bulletin de Physio-pathologie Respiratoire*, **9**, 925.
- Yernault, J. C., Baran, D., Englert, M., and Derckx, C. (1972). Un programme partiellement automatisé d'étude fonctionnelle pulmonaire. Application chez l'adulte et l'enfant. *Acta Tuberculosa et Pneumologica Belgica*, **63**, 110.
- and Englert, M. (1974). Static mechanical lung properties in young adults. *Bulletin de Physio-pathologie Respiratoire*, **10**, 435.
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