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Assisted ventilation using cuirass respirators

W. Kinnear*, M. Petch**, G. Taylor**, J. Shneerson*

Assisted ventilation using cuirass respirators. W. Kinnear, M. Petch, G. Taylor, J. Shneerson.
ABSTRACT: The effects of cuirass-assisted ventilation have been studied in 25 subjects with chest wall disease. Cuirass respirators increase ventilation in proportion to the peak negative pressure within the cuirass shell and the respiratory rate. Positive pressure applied during expiration produces little additional ventilation. During cuirass-assisted ventilation end-expiratory volume increases, arterial carbon dioxide tension (Pa_{CO_2}) falls and arterial oxygen tension (Pa_{O_2}) rises. Cardiac output is unchanged. Paradoxical chest wall motion is corrected by cuirass-assisted ventilation and restriction of chest wall expansion by the cuirass shell is minimal. Jacket-type respirators can produce larger tidal volumes than the cuirass at the same peak negative pressure, but are associated with greater air leakage.
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* The Assisted Ventilation Unit, Newmarket General Hospital, Suffolk, England.
** The Cardiac Unit, Papworth Hospital, Huntingdon, Cambridgeshire, England.

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Nocturnal hypoventilation can be corrected by a variety of methods of assisted ventilation [12]. If hypoventilation is the result of upper airway obstruction, continuous positive airway pressure can be applied through a nasal mask. Intermittent positive pressure ventilation via a nasal mask has been used in patients with neuromuscular disease [10], but is more usually employed with a tracheostomy. In the absence of upper airway obstruction, other methods of providing assisted ventilation may be used. Postural ventilation using a rocking bed and electrophrenic respiration are generally only suitable for use in patients with normal lung and chest wall mechanics [12]. External negative pressure ventilation can be used in the form of a tank ventilator (iron lung), a jacket respirator or a cuirass respirator. Cuirass respirators are the simplest form of external negative pressure ventilator, consisting of a single rigid shell which fits over the thorax anteriorly. They can be used easily at home by the unaided patient, can be transported in a small car, and are relatively cheap. We have investigated some effects of cuirass respirators in patients with chest wall disease.

Subjects and methods

Twenty-five subjects with chest wall disease were studied. Details of these subjects are given in table 1. Forced vital capacity (FVC) and forced expiratory volume in one second (FEV_1) were measured using a Vitalograph wedge spirometer. End-expiratory volumes (EEV) were measured by helium dilution. Residual volume (RV) and total lung capacity (TLC) were calculated from EEV, expiratory reserve volume and inspiratory capacity. Tidal volumes (VT) were taken as the mean of five breaths recorded on a PK Morgan wet spirometer. Arterial blood was sampled from the radial artery and analysed in a Radiometer blood gas analyser. Ribcage and abdominal motion were assessed using a Respitrace inductance plethysmograph, calibrated by the isovolume technique [18]. The same posture was maintained during spontaneous and cuirass-assisted ventilation, and calibration was checked by comparison of the sum of the ribcage and abdominal signals with the volume signal from a PK Morgan dry spirometer.

In eight patients a flow-directed balloon catheter was introduced into the pulmonary artery. Cardiac output was measured by thermodilution using this catheter in conjunction with an Instrumentation Laboratories cardiac output computer. The mean of three injections of 10 mls of cold saline was used in the calculation of cardiac output.

Individual cuirass respirator shells were constructed in Vitrathine from plaster casts of each patient [2]. The edges were padded with foam and covered in Neoprene rubber to provide a seal (fig. 1). The cuirass shell fits over the patient's chest and abdomen anteriorly with the sides resting on the bed. It is held in place by a Neoprene strap passing behind the patient. A connector is positioned on the cuirass shell anteriorly and a 2 metre long, 35 mm internal bore, connecting tube led from the inside of the cuirass shell to the negative pressure pump. A Newmarket pump (Si Plan Electronics Research Ltd) was used to generate positive and negative pressure (fig. 2), [11]. This uses an industrial fan rotated by an electric motor. The negative pressure side of the fan is opened intermittently by a rotary valve to the inside of the cuirass. A signal generator controls an electric motor and associated gearbox, which actuate the rotary valve. Respiratory rate and peak negative pressure can be altered using the signal generator, and positive pressure may be used, during the expiratory

Table 1. - Mean (SD) age, sex and spirometry and arterial blood gases of subjects at initial presentation.

Disease	Male	Female	Age yr	FVC *l*	FEV$_1$/FVC %	Pao$_2$ kPa	Paco$_2$ kPa
Scoliosis	4	3	51.6 (6.8)	0.92 (0.20)	72 (15)	7.2 (1.5)	8.1 (0.8)
Thoracoplasty	3	7	62.7 (5.5)	1.30 (0.65)	46 (7)	7.5 (2.1)	7.1 (1.2)
Neuromuscular	6	2	37.1 (23.3)	1.18 (0.70)	78 (22)	9.6 (1.9)	7.9 (1.9)

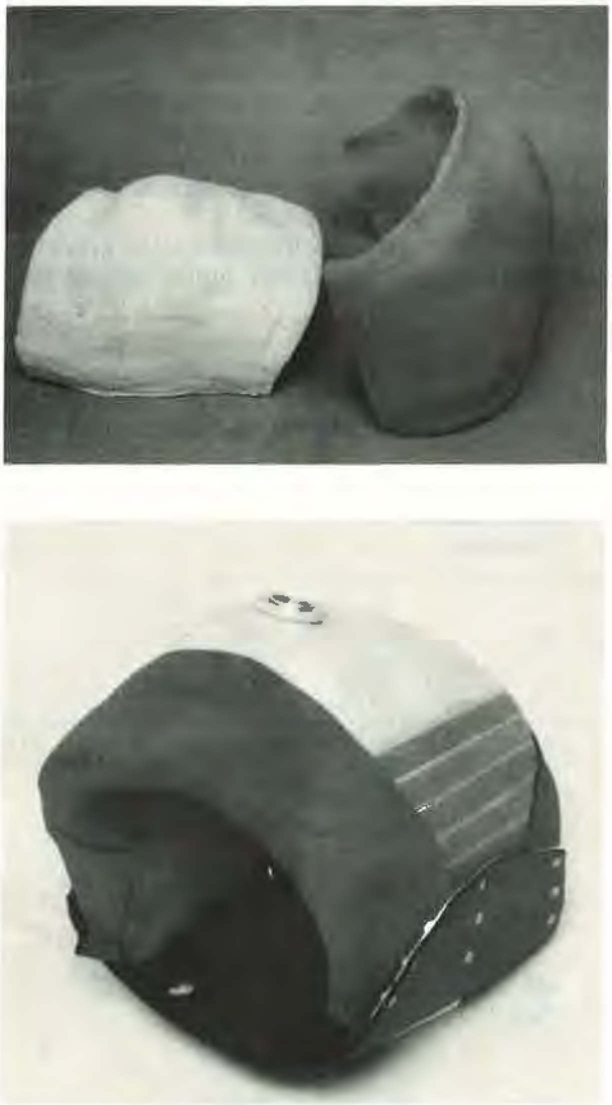

Fig. 1. a: The built-up plaster cuirass and moulded Vitrathine shell. b: The completed cuirass.

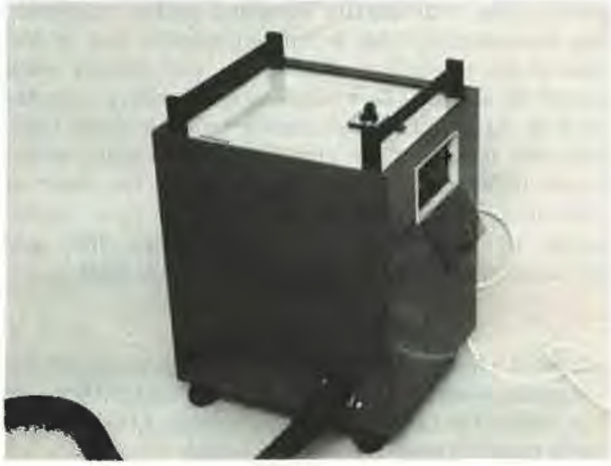

Fig. 2. The Newmarket Pump.

phase of the cycle, by opening the positive pressure side of the fan to the inside of the cuirass.

The pressure inside the cuirass shell was measured using a Si Plan Electronics Research Ltd differential pressure transducer, with atmospheric pressure as the reference pressure except in the measurement of the pressure drop down the connecting pipe, when the pressure inside the cuirass shell was compared to the pressure at the pump inlet. A Mercury Electronics factory calibrated high flow pneumotachograph head was inserted between the pump inlet and the connecting pipe. Pump flow at different external negative pressures was recorded during the end-inspiratory pressure plateau produced by a square pressure waveform.

Tidal volume (VT) was measured at rest and at peak negative intra-cuirass pressures of 10, 20, 30 and 40 cm of water, both with and without the maximum positive pressure which could be produced inside the cuirass shell during expiration. An inspiratory/expiratory ratio of 1/1 was used in all studies, with a respiratory rate of fifteen breaths per min except in the assessment of the effect of respiratory rate on minute volume. In the studies of respiratory rate, end-expiratory volume, chest wall motion, arterial blood gases and cardiac output, a peak external negative pressure of 30 cm of water was used without external positive pressure. In the studies involving positive expiratory pressure, the maximum positive pressure which could be achieved inside the cuirass shell was used. In all cases this was less than 15 cm of water.

The individually constructed cuirass respirator shells were compared with three other external negative pressure respirators of the jacket type. The Tunnicliffe jacket consists of a backplate and anterior perspex plate covering the chest and upper abdomen. The anterior plate extends up to the supraclavicular region and does not touch the chest or abdomen. An airtight seal is produced by a nylon jacket sealed around the neck, arms and waist. The Emerson respirator consists of a backplate and an anterior shell which extends from the supraclavicular region to the lower abdomen. The anterior shell does not touch the chest or abdomen and an airtight seal is provided by a similar nylon jacket to that used in the Tunnicliffe jacket. The individually moulded jacket respirator was constructed from a built-up plaster cast of the patient in a similar manner to the cuirass shell described above. The Vitrathine shell covers a similar area of the chest and abdomen to the cuirass shell, from the region of the manubriosternal angle to the lower abdomen, but it does not touch the chest or abdomen. An airtight seal is produced by a similar jacket to that described for the Tunnicliffe and Emerson respirators, but no backplate is used.

Results are expressed as mean (standard deviation). Statistical analysis was carried out using the INSTAT statistical package produced for the BBC B microcomputer by the Department of Applied Statistics at the University of Reading. Statistical significance was tested using paired and unpaired t-tests.

Results

The tidal volumes obtained at different peak external negative pressure (PENP) are given in table 2. For the group as a whole, VT was significantly greater than during spontaneous ventilation at all PENP ($p < 0.05$), and each 10 cm of water increment in peak external negative pressure produced a significant increase in VT ($p < 0.05$).

The bottom line of table II gives the VT obtained using the same PENP but with the addition of external positive expiratory pressure (EPEP). The VT on addition of EPEP were significantly higher than with external negative pressure alone using a PENP of 10 and 20 cm of water ($p < 0.05$), but there was no significant difference in VT on addition of EPEP to a PENP of 30 or 40 cm of water.

For the fifteen patients investigated, the mean (SD) end-expiratory volume (EEV) during spontaneous

Table 2. - Mean (SD) tidal volumes in mls during spontaneous and cuirass-assisted ventilation at different peak external negative pressures, using a respiratory rate of 15 breaths per minute and an inspiratory time of 2 s. The figures obtained on addition of external positive pressure (EPP) during expiration are included at the bottom of the table (†=greater than with negative pressure alone, $p < 0.05$).

		Spontaneous Ventilation	Cuirass-assisted Ventilation			
Peak External Negative Pressure cmH$_2$O		0	10	20	30	40
Scoliosis		285	340	367	356	401
		(81)	(79)	(97)	(79)	(73)
	n	7	7	7	5	2
Thoracoplasty		397	492	523	588	518
		(112)	(242)	(214)	(258)	(165)
	n	8	7	8	7	5
Neuromuscular		380	410	485	533	620
		(337)	(260)	(254)	(220)	(299)
	n	8	8	8	5	3
All subjects		357	414	462	503	525
		(211)	(212)	(205)	(221)	(197)
	n	23	22	23	17	10
All subjects: on addition of EPP			494†	520†	566	569
			(227)	(232)	(241)	(240)
			20	22	16	10

Table 3. - Mean (SD) minute volumes in litres during cuirass-assisted ventilation using different respiratory rates, with a peak external negative pressure of 30 cm of water and an inspiratory/expiratory ratio of 1 / 1.

Respiratory rate/min	10	15	20	25	30
Scoliosis	5.37	7.86	9.33	10.72	9.16
(n=5)	(2.37)	(3.59)	(5.45)	(7.18)	(2.08)
Thoracoplasty	7.22	8.14	9.56	11.39	13.03
(n=8)	(3.05)	(3.26)	(4.20)	(4.81)	(6.02)
Neuromuscular	6.24	7.92	9.45	9.40	11.21
(n=6)	(4.11)	(4.21)	(6.11)	(6.57)	(6.35)
All subjects	6.37	7.99	9.46	10.59	10.86
(n=19)	(3.16)	(3.47)	(4.91)	(5.85)	(5.82)

ventilation was 1.29 (0.66) *l*, and during cuirass-assisted ventilation using external negative pressure alone was 1.50 (0.83) *l* ($p < 0.05$). On addition of EPEP, the EEV fell to 1.35 (0.79) *l* ($0.1 > p > 0.05$).

The minute volumes obtained at different respiratory rates are given in table 3. Each increase in rate of five breaths per minute produced a significant increase in minute volume ($p < 0.05$).

During spontaneous ventilation, two patients with neuromuscular disease, two with scoliosis and one with a thoracoplasty had paradoxical inward movement of the abdomen during inspiration. Two patients with a thoracoplasty had paradoxical motion of the ribcage during spontaneous ventilation. Respitrace analysis of ribcage and abdominal motion in these patients demonstrated synchronous expansion of both the ribcage and abdomen during cuirass-assisted ventilation.

Daytime Pa_{CO_2} for the sixteen patients studied was 6.8 (0.9) kPa during spontaneous ventilation and 6.2 (1.3) kPa during cuirass-assisted ventilation ($p < 0.01$). Daytime Pa_{O_2} for these patients was 8.7 (2.2) kPa during spontaneous ventilation and 9.2 (2.4) kPa during cuirass-assisted ventilation ($p < 0.05$).

The mean (SD) cardiac output for the eight patients studied was 4.5 (1.3) *l*/min during spontaneous ventilation, and 4.3 (1.3) *l*/min during cuirass-assisted ventilation ($p > 0.1$).

The flow rates required to produce different peak external negative pressures during cuirass-assisted ventilation are shown in figure 3. The pressure drop down the 2 metre length of tubing was linearly related to flow down the tube when measured over the range of 300–1500 *l*/min, being approximately 0.5 cm of water per 100 *l*/min of flow.

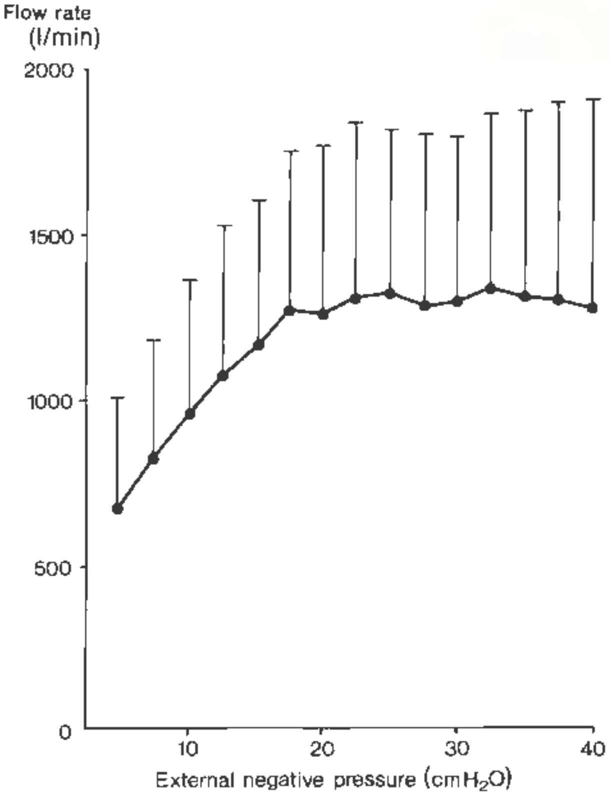

Fig. 3. Pump flow rates at different peak external negative pressures during cuirass-assisted ventilation. Mean and standard deviation for ten patients.

Table 4. - Tidal volumes (VT) obtained at different peak external negative pressures (PENP) using four respirators (†=greater than cuirass at the same PENP, p<0.05).

	PENP cmH$_2$O	10	20	30	40
Cuirass		429	472	516	568
		(176)	(175)	(220)	(190)
	n	12	13	13	7
Tunnicliffe		478	525†	483	473
		(218)	(212)	(105)	(33)
	n	11	11	10	4
Emerson		458	543†	625†	467
		(218)	(256)	(292)	(8)
	n	10	10	6	2
Moulded Jacket		437	518	544	359
		(162)	(235)	(258)	(61)
	n	11	11	8	2

Mean ± (SD)

The VT using the cuirass, Tunnicliffe, Emerson and individually moulded jacket respirators at different PENP are given in table 4. The VT/PENP relationships for these four respirators are shown in figure 4. The pump was unable to generate PENP of greater than 20 cm of water in every subject, and where the PENP was achieved in less than five subjects the points are omitted from figure 5. The Tunnicliffe jacket produced significantly larger VT than the cuirass at PENP of 20 cm of water ($p < 0.05$) but not

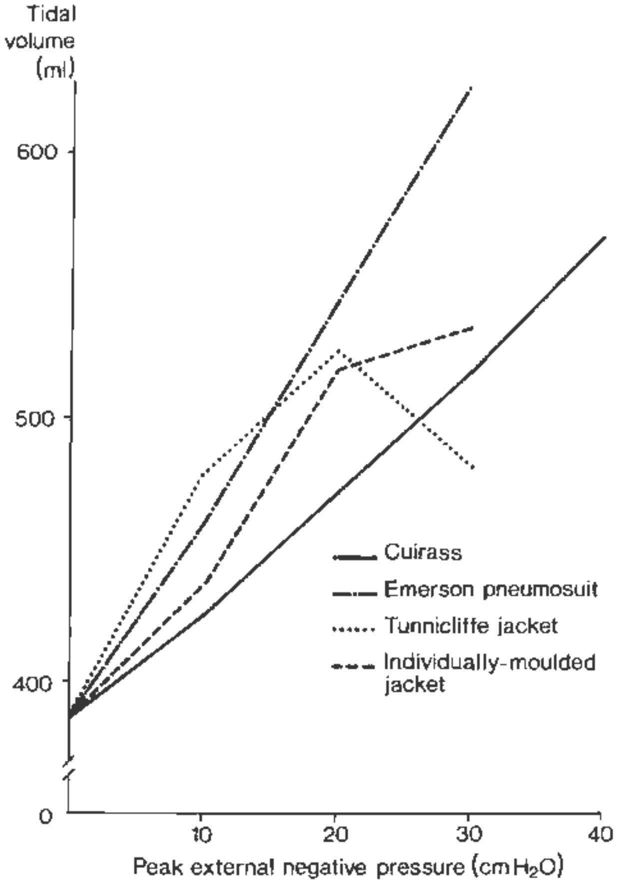

Fig. 4. The relationship between peak external negative pressure and tidal volume for four external negative pressure respirators.

at other PENP. The VT obtained with the moulded jacket were not significantly different from those obtained with the cuirass at any PENP. The Emerson respirator produced VT significantly larger than those obtained with the cuirass at PENP of 20 and 30 cm of water ($p < 0.05$).

Discussion

In the middle decades of this century, cuirass respirators were developed for use in the management of poliomyelitis with respiratory muscle involvement [3, 5, 15, 17]. More recently, their value in the management of hypoventilation in patients with other diseases of the chest wall has been recognised [6, 7, 9, 13, 14, 16, 19]. Standard cuirass shells are often unsuitable for use in patients with chest wall deformity [7, 16, 19], and a cuirass shell moulded to the shape of the patient's thorax is required [1, 7, 13, 16, 19]. We used a simple technique to construct cuirass shells individually shaped to each patient. Ventilation increased during cuirass-assisted ventilation using these shells in proportion to the PENP produced inside the shell and to the respiratory rate. This increase in ventilation was reflected by a decrease in Pa_{CO_2}. Previous studies of cuirass respirators have demonstrated improvement in Pa_{CO_2} during cuirass-assisted ventilation in scoliosis [7, 13, 16] and neuromuscular disease [14].

Use of a cuirass shell strapped round the chest might be expected to reduce EEV, although previous reports of the effect of cuirass respirators on EEV are conflicting [4, 5]. The increase in EEV seen in our patients during cuirass-assisted ventilation could be artefactual as a result of improved mixing of helium with the increase in ventilation. It could reflect premature termination of expiration during cuirass-assisted ventilation with an expiratory time which was too short. Expiratory muscle activity may be present at resting EEV in patients with chest wall disease, and abolition of active expiration could also explain the increase in EEV. The increase in Pa_{O_2} seen during cuirass-assisted ventilation in our patients may have been related to the increase in EEV, with improved ventilation-perfusion matching.

EPEP during cuirass-assisted ventilation has been shown to produce a small increase in tidal volume [3, 4] and a decrease in EEV [5]. In our patients the increase in VT on addition of EPEP was only significant with a PENP of 10 and 20 cm of water, and was associated with a fall in EEV. EPEP lifted the cuirass away from the patient and increased the leak around the rim of the shell. EPEP was uncomfortable for most patients and none used it at night in the long term.

Previous studies, using cinefluorography in animals and carotid thermography in man, have suggested an increase in cardiac output during cuirass-assisted ventilation [8]. External negative pressure around the thorax should increase venous return from the peripheries, although venous return from the legs may be restricted by compression of the lower abdomen by the lower rim of the cuirass. With a cuirass shell covering the abdomen, pooling of blood in the abdomen could occur during the negative pressure phase of the pump cycle. Pulmonary vascular resistance will be increased by lung inflation but may decrease with improved oxygenation, which can also improve myocardial contractility. Lowering of Pa_{CO_2} may produce vasoconstriction. We did not demonstrate a significant change in cardiac output during cuirass-assisted ventilation. The magnitude of change of Pa_{O_2} or Pa_{CO_2} seen in our patients was unlikely to produce a significant effect on cardiac output. During cuirass-assisted ventilation, blood cannot be sampled from the femoral arteries and sampling from the radial or brachial arteries proved difficult in these patients. Arterial blood gases were measured at the same time as cardiac output in an insufficient number of patients for conclusions to be drawn about oxygen delivery during cuirass-assisted ventilation, but the improvement in Pa_{O_2} described above would suggest a small increase in systemic oxygen delivery despite the absence of change in cardiac output.

There is considerable leakage of air into the shell around the edges of the cuirass when there is a negative pressure within the cuirass shell. During cuirass-assisted ventilation, this leakage depends on the PENP used, and also on the position of the patient. At the pump flow rates required, there is an appreciable fall in pressure down the connecting tube, and it is therefore essential to measure the pressure within the cuirass shell in any study of cuirass-assisted ventilation.

The use of a cuirass shell which covers the chest and abdomen corrects paradoxical motion of part of the chest wall. The cuirass shell may restrict expansion of the chest wall where the edges seal onto the patient. The Tunnicliffe jacket covers more of the upper ribcage than the cuirass, but less of the abdomen, and the fall in VT on increasing the PENP from 20 to 30 cm of water may reflect restriction of abdominal expansion. The Emerson respirator covers a larger area than any of the other respirators, and produced the largest VT. The shell of the individually moulded jacket respirator covers a similar area of the patient to the cuirass but does not touch the chest wall. The tidal volumes obtained with this respirator were not significantly greater than with the cuirass, suggesting that restriction of expansion of the chest wall by the cuirass is minimal.

The pump was only able to generate a PENP of 40 cm of water in the cuirass in 58% of subjects. The greater leaks with the other external negative pressure respirators restricted this PENP to 36% of patients using a Tunnicliffe jacket, 20% of patients using the Emerson respirator and 18% using a moulded jacket respirator. Thus although for any PENP the jacket respirators produced a larger VT, the largest VT was obtained with the cuirass in one third of patients on account of the greater PENP which could be obtained.

Conclusions

The cuirass respirators used in this study produced an increase in tidal volume and end-expiratory volume, a reduction in $Paco_2$, a rise in Pao_2, no change in cardiac output, and synchronous ribcage and abdominal expansion. An individually designed cuirass respirator increases ventilation in most subjects with chest wall disease who require external negative pressure ventilation. It is cheaper and much easier for the patient to use than any of the jacket respirators, which should be reserved for the small number of patients in whom a cuirass is not effective.

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RÉSUMÉ: Les effets d'une ventilation assistée à l'aide d'une cuirasse ont été étudiés chez 25 sujets atteints d'une maladie de la paroi thoracique. Les respirateurs de type cuirasse augmentent la ventilation proportionnellement à la dépression maximale intra-cuirasse et à la fréquence respiratoire. Une pression positive appliquée pendant l'expiration n'augmente que faiblement la ventilation. Pendant la ventilation le volume de fin d'expiration augmente, $Paco_2$ chute et Pao_2 s'accroît: le débit cardiaque reste inchangé. Les mouvements paradoxaux de la paroi bronchique sont corrigés sous cuirasse, laquelle ne limite que très peu les possibilités d'expansion de la cage thoracique. Les respirateurs de type jaquette peuvent produire de plus grands volumes courants que la cuirasse, mais sont aussi associés avec des fuites aériques supérieures.