A MODEL LUNG WITH THE CAPACITY FOR SIMULATED SPONTANEOUS BREATHING


SUMMARY
A model lung is described which can be ventilated artificially but which also has the capacity to breathe spontaneously at pre-determined rate and depth. It appears particularly suitable for studying the performance of ventilators which interact with the patient, including those with the facility for triggering, synchronization and mandatory minute ventilation. An additional facility is the blocking of a simulated spontaneous inspiration during an artificial inflation ("Hering–Breuer reflex").

Certain of the more modern artificial ventilators, particularly those used in the intensive care unit, interact with the patient such that the volume or pattern, or both, of the artificial ventilation are modified according to any attempt the patient may make to breathe spontaneously.

Some of these ventilators adjust the timing of the artificial breaths to the patient's own attempts by means of triggering which may be used for synchronization. Others use mandatory minute volume (MMV) (Hewlett, Platt and Terry, 1977) which maintains a constant minimal minute volume whatever spontaneous minute volume the patient is able to achieve. As the patient increases his minute volume, the ventilation produced by the machine is decreased. If the patient breathes as much or more than the MMV setting, the artificial breaths are discontinued. If, however, the patient's breathing is decreased below the MMV or ceases altogether, the ventilator resumes its action instantly.

These interactions are complex and it is difficult to assess such apparatus on the laboratory bench with existing model lungs. In addition, it is not easy to assess these machines in clinical use. As a result, a model lung has been constructed which can be ventilated artificially and which can also "breathe" by itself. The model described here is an improvement on a prototype presented previously to the Anaesthetic Research Society (Lyle, Hewlett and Nunn, 1983).

The current version of the apparatus is shown in figure 1. The right-hand bellows simulate the patient's lung. Changes in their volume are recorded on one channel of a Servoscribe pen recorder by a signal from a linear rotary potentiometer attached to the pivot of the arm fixed to the top of the model lung. This arm is extended beyond the bellows and can be lifted by the left-hand bellows which represent the diaphragmatic contraction of spontaneous breathing. The model lung bellows are reinforced by steel rings which prevent collapse of the corrugations during "spontaneous" inspiration against increased airway resistance. The "functional residual capacity" is 650 ml but, if necessary, this can be increased by modification of the mounting of those bellows which represent the patient's lungs. The sliding counterweight shown to the right of figure 1 serves to match the functional residual capacity to the relaxed position of those bellows which represent diaphragmatic contraction.

The left-hand bellows are connected to a wishbone suspension arm which actuates a second potentiometer providing an electrical output corresponding to attempts by the patient to breathe spontaneously. The left-hand bellows are moved by compressed air which is admitted to the bellows through a variable resistor by a solenoid valve controlled by an adjustable electronic timing circuit (fig. 2). During expiration, air escapes passively from the bellows through a variable resistor.

A demonstration of the model lung in inspiration produced by an artificial ventilator is depicted in figure 1. The expiratory position of the left-hand bellows indicates the the "patient" is paralysed and apnoeic.

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Fig. 1. Present version of the model lung. The right-hand bellows represent the lung, while the left-hand bellows act as a driver representing diaphragmatic contraction. Electronic and pneumatic circuits are contained in the base of the apparatus (fig. 2). The lung is shown in the course of an artificial inflation with the driver bellows in the expiratory position.

Signal lamps
Output to chart recorder
"Lung volume" >"Inspiratory muscle drive"
Spontaneous "breathing"
Expiration Inspiration

Driver bellows position sensor
"Lung volume sensor"

"Hering-Breuer reflex" On/Off
Exp. timer
Insp. timer
Respiratory rate

Compressed air at 4 bar
Inspiratory flow rate control
Expiratory flow rate control
Diaphragm valve
"Lung volume sensor"

Sensors and display
"Hering-Breuer reflex"
Circuit for "spontaneous breathing"

"Lung volume sensor"

Fig. 2. The centre section of this diagram shows the electronic circuitry which controls the pattern of "spontaneous breathing". This is actuated through the pneumatic circuit on the right which inflates the driver bellows and so expands the "lung". The position of the driver bellows and the "lung volume" are sensed with potentiometers and lung inflation without corresponding movement of the driver bellows inhibits "spontaneous inspiration" ("Hering-Breuer reflex"). A1, A2 = amplifiers; C = comparator; S1, S2 = solenoid valves (armatures move to the left during inspiration and to the right during expiration).
Airway pressure can be measured on either side of the simulated (and variable) airway resistance, corresponding to airway and alveolar pressures. The pressure–flow rate characteristics of the three resistances provided are shown in figure 3. The lowest resistance is comparable to that of an anaesthetized patient plus a tracheal tube. "Alveolar" and "tracheal" pressures can be measured at the points shown in figure 1. Static compliance can be varied by movement of a spring along the arm of the model lung, the full range being 25–70 ml cm H₂O⁻¹. Spontaneous inspiratory and expiratory times can be varied between 0.22 and 2.3 s (inspiration) and 0.5 and 10.6 s (expiration) giving a range of frequencies between 84 and 4.6 b.p.m. The tidal volume is infinitely variable up to a maximum of 1200 ml at a respiratory frequency of 13 b.p.m. or less.

The prototype of the model lung could make a "spontaneous" inspiration during the course of an artificial inflation. However, not only is this unlikely to occur during life, but it complicates greatly the calculation of spontaneous and artificial ventilation, the sum of which might appear to be different from the actual total (Bushman, personal communication). Therefore we have incorporated, in the present model, a facility by which the solenoid valve controlling a simulated spontaneous inspiration is prevented electrically from opening whenever the...
right-hand bellows are inflated above the level of the left-hand bellows (fig. 2). In this mode, spontaneous inspiration is inhibited by positive end-expiratory pressure and, therefore, a switch is provided to inactivate the "Hering–Breuer reflex".

Typical traces obtained from the model lung when connected to two separate ventilators each of which has the capacity to interact with the patient are shown in figures 4 and 5. The "Hering–Breuer reflex" was inoperative when these traces were obtained. The apparently increased "diaphragmatic effort" with certain breaths during the first 2 min (fig. 5) is the result of the random coincidence of a spontaneous breath with an artificial breath and the consequent decrease in resistance to the ascent of the driver bellows. This is attributable to the lack of a spindle mechanism in the driver system and may be used as an indicator of coincidence of spontaneous and artificial breaths.

**REFERENCES**


**UN MODELE DE POU MON QUI PUISSE SIMULER LA VENTILATION SPONTANEE**

**RESUME**

On trouvera ici la description d'un modèle de poumon qui peut être ventilé artificiellement mais qui peut également respirer spontanément, à une fréquence et une amplitude prédéterminées. Il semble convenir particulièrement à l'étude des performances de respirateurs qui interagissent avec le patient, y compris ceux qui permettent le déclenchement, la synchronisation, et la ventilation obligatoire intermittente (IMV). Un avantage supplémentaire est obtenu par l'arrêt d'une inspiration spontanée simulée au cours d'une insufflation artificielle ("réflexe d'Hering–Breuer").
EIN LUNGENMODELL ZUR SIMULATION VON SPONTANATMUNG

ZUSAMMENFASSUNG
Es wird ein Lungenmodell beschrieben, das künstlich beatmet werden kann, jedoch auch zur Spontanatmung mit einstellbarer Frequenz und Tiefe fähig ist. Es ist besonders geeignet zur Untersuchung der Funktion von Beatmungsgeräten, die vom Patienten beeinflusst werden können, einschließlich derer mit Vorrichtungen zur Triggerung, Synchronisation und zu einstellbarem Minutenvolumen. Eine zusätzliche Möglichkeit ist das Blocken einer simulierten spontanen Inspiration während künstlicher Beatmung (Hering-Breuer-Reflex).

UN PULMON MODELO CON CAPACIDAD DE RESPIRACION ESPONTANEA SIMULADA

SUMARIO
Se describe un pulmón-modelo que puede ventilarse artificialmente pero que al mismo tiempo posee la capacidad de respirar espontáneamente según una profundidad y un ritmo pre-determinados. Parece particularmente adaptado para estudiar el rendimiento de ventiladores que inter-actuan con el paciente, inclusive los que disponen de un dispositivo para arrancar, sincronizar y controlar la ventilación. Un dispositivo adicional consiste en el bloqueo de una inspiración espontánea simulada durante una inflación artificial ("Reflejo Hering-Breuer").