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# Introduction to a new inspiratory threshold loading device

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**ABSTRACT: Inspiratory threshold loading is an important tool in assessing inspiratory muscle function and has been widely used in studies of respiratory mechanics. A simple system was designed to provide a pure and precise inspiratory threshold load.**

**The inspiratory threshold loading system comprises a flow generator attached *via* a pressure chamber, to the inspiratory port of a Hans-Rudolph valve. By limiting the circulation of air generated by the flow generator between the room and the pressure chamber, different levels of negative pressure are produced in the pressure chamber and applied to the inspiratory valve. An inspiratory pressure equal to the negative pressure in the chamber has to be generated to open the inspiratory valve for flow. The system was tested in four subjects by measuring mouth pressure ($P_{m}$), threshold pressure ($P_{th}$) and valve resistance ($R$). The $P_{m}$ at the beginning of inspiratory flow was defined as the opening pressure ($P_{op}$).**

**The $P_{th}$ was constant throughout inspiration. $P_{op}$ was linearly related to $P_{th}$ ($p<0.0001$), with slopes within 2% of identity and intercepts within ±0.2 $cmH_2O$. $R$ was between 0.7–1.1 $cmH_2O \cdot L^{-1} \cdot s^{-1}$ under all conditions and was independent of both $P_{th}$ ($p=0.76$) and inspiratory flow ($p=0.24$).**

**The results demonstrate that this system can provide a constant inspiratory threshold load throughout inspiration with little flow resistance, and is therefore ideal for respiratory studies.**

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Inspiratory threshold loading is a very effective strategy for loading the inspiratory muscles, as it guarantees a predetermined inspiratory pressure to be developed before the start of inspiratory flow. Hence, inspiratory threshold loading has been used not only for inspiratory muscle endurance testing and training [1–3] but also for studies on the control of breathing [4–6].

The inspiratory threshold loading device most often used is the weighted plunger introduced by NICKERSON and KEENS [7]. With this system, the subject has to generate sufficient inspiratory pressure to lift the weight, in order to open the inspiratory valve for flow. In spite of the recent modifications to the inspiratory valve design for this system [8], the dependence of the threshold pressure on flow has not been completely eliminated.

In this paper, a new inspiratory threshold loading device is presented, which is based on a constant negative pressure applied to the inspiratory side of a Hans-Rudolph two-way nonrebreathing valve. This simple system provides stable threshold pressure as desired and the additional flow resistance is minimal.

## Methods

### *Design of the threshold loading device*

The new inspiratory threshold loading system is composed of a powerful vacuum cleaner (Hoover Canada, Burlington, Ontario, Canada), directly attached, through a pressure chamber, to the inspiratory port of a Hans-Rudolph two-way nonrebreathing valve (type 2700, Hans Rudolph, Kansas City, USA) (fig. 1). The pressure chamber is cylindrical in shape (48 cm long and 6.5 cm in diameter) and is made of Plexiglass. The flow generator sucks a constant flow of air out of the pressure chamber. Air circulates between the room and the pressure chamber through an adjustable resistance, creating a constant negative pressure in the pressure chamber. The inlet of the pressure chamber is composed of multiple holes with different sizes. The resistance of the inlet to flow, which establishes the desired negative pressure in the pressure chamber, is created and adjusted by selectively obstructing different combinations of the holes. The negative pressure in the chamber is determined by the product of the resistance at the inlet of the pressure chamber and the flow gen-

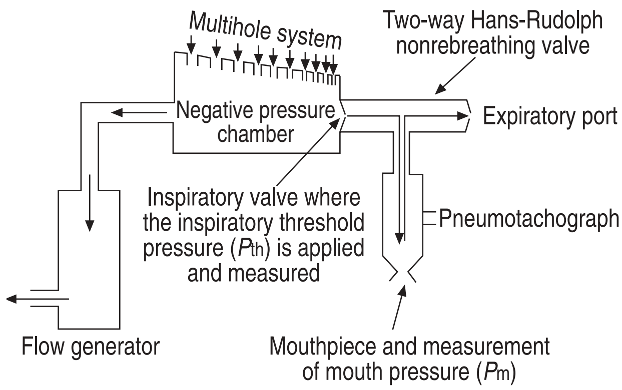


Fig. 1. – Schematic illustration of the negative pressure system for inspiratory threshold loading.

erated by the flow generator, and in theory can be varied to any level desired. The negative pressure produced in the pressure chamber is applied directly to the inspiratory port of the Hans-Rudolph valve and serves to close the inspiratory valve, and therefore provides the inspiratory threshold load. A negative pressure equal to the negative pressure in the pressure chamber has to be generated in the mouth side of the port by the inspiratory muscles before the inspiratory valve can be opened and the inspiratory flow can be initiated. Since the flow produced by the flow generator is much larger than the inspiratory flow, the negative pressure in the chamber or the inspiratory threshold load is constant throughout the whole inspiration and independent of inspiratory flow. The respiratory system is not directly exposed to the negative pressure in the pressure chamber, as this negative pressure has already been cancelled out by the inspiratory effort before the inspiratory valve opens.

*Experimental procedures*

Four seated laboratory staff volunteered to breathe through the mouthpiece connected to the inspiratory threshold loading system. Respiratory flow was measured by a pneumotachograph (Fleisch no. 3, Lausanne, Switzerland) attached between the Hans-Rudolph valve and the mouthpiece. Mouth pressure ($P$m) and the inspiratory threshold pressure ($P$th) were measured by two differential pressure transducers (Validyne, Northridge, CA, USA) as shown in figure 1. $P$th represents the negative pressure applied to the inspiratory valve by the pressure chamber. The $P$m at the beginning of inspiratory flow was defined as the opening pressure ($P$op). $P$op was related to $P$th, and the flow resistance of the system, during flow, was calculated as the difference between $P$m and $P$th divided by flow. Both pressure and flow signals were amplified, passed through an analogue-to-digital converter and recorded on a computer.

The data were collected during quiet, unloaded breathing and during inspiratory threshold loading with the pressure varied between 0 and -35–-40 $cmH_2O$. The different threshold pressures were applied randomly and the subjects did not know the level of pressure during loading. At each level of load, approximately 2 min of data were acquired. The subjects were also asked progressively to increase their inspiratory flow during each loading session to test whether the inspiratory threshold load was dependent on the inspiratory flow.

The results were expressed as mean±SD. Statistical analysis was conducted by analysis of variance and least square regressions.

## Results

Respiratory flow, threshold pressure and mouth pressure, from a representative tracing of one subject are shown in figure 2 for different levels of inspiratory threshold load. During loading, $P$m is generated before the development of inspiratory flow. Once $P$m becomes less than the applied $P$th, inspiratory flow starts. The applied $P$th was constant, indicating that the threshold load was constant throughout the whole inspiration. During the period of inspiratory flow, the $P$m was a little more negative than the applied $P$th, reflecting the flow resistance of the apparatus.

Figure 3 shows the relationships between the opening and applied threshold pressures for each subject. The slopes of the relationships were between 0.98–1.01 and the intercepts were within ±0.2 $cmH_2O$, with regression coefficients always >0.99 (p<0.0001).

The valve resistance of the inspiratory threshold load device during flow was plotted both as a function of the magnitude of the applied $P$th and as a function of the mean inspiratory flow. As shown in figure 4, under all conditions, the resistance was between 0.7–1.1 $cmH_2O \cdot L^{-1} \cdot s^{-1}$, independent of both $P$th (p=0.76) and inspiratory flow (p=0.24).

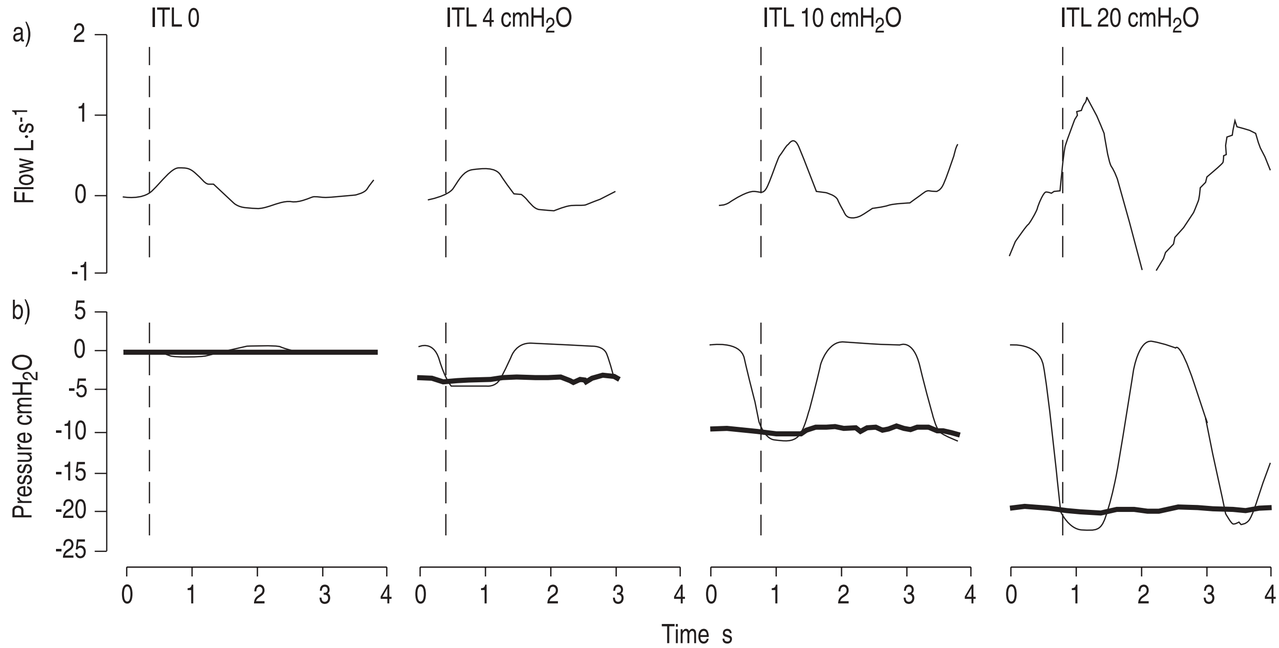


Fig. 2. – Representative tracings of a) respiratory flow, b) applied threshold pressure (thick curve) and mouth pressure (thin curve) from one subject for increasing inspiratory threshold load (ITL). The curves were derived from the average of several breaths. The vertical dashed line indicates the beginning of inspiratory flow.

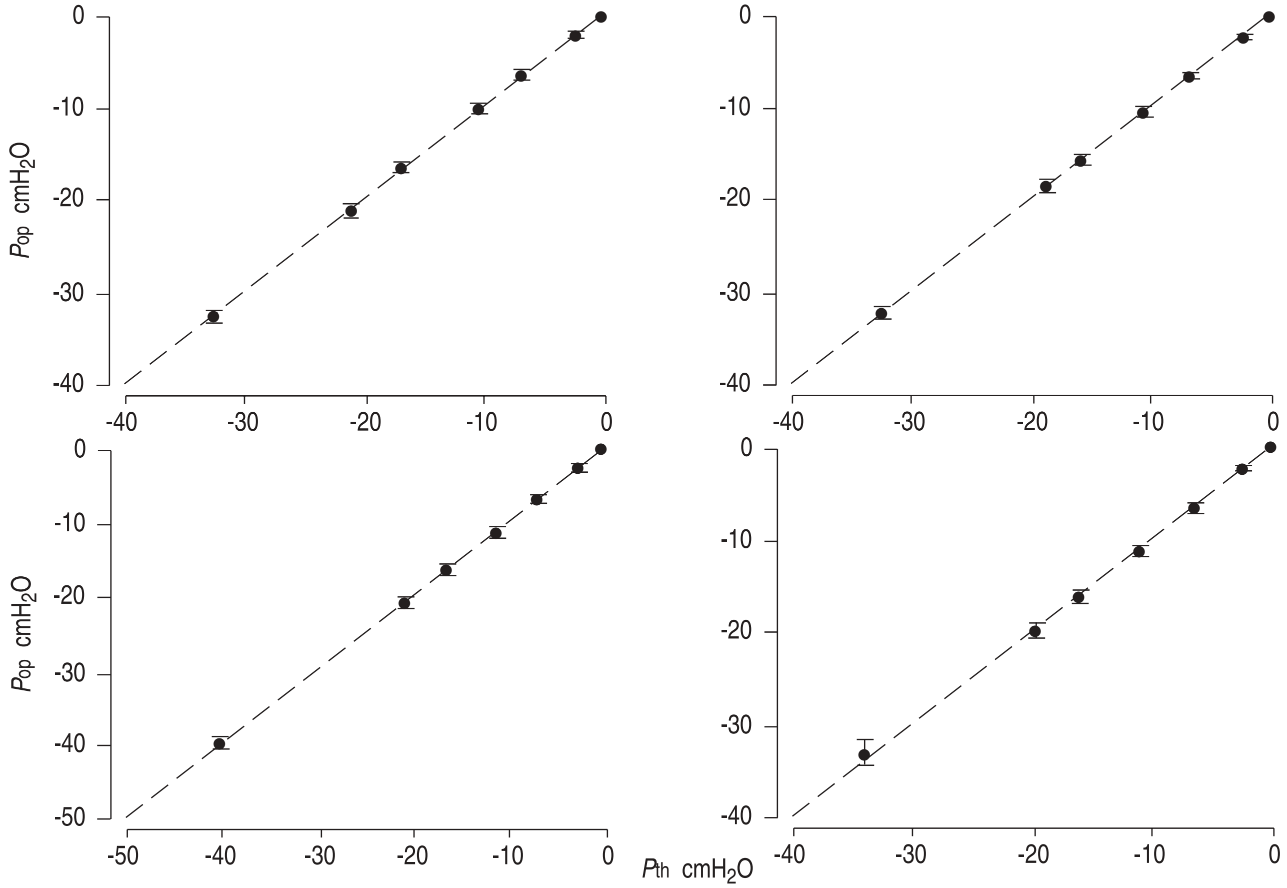


Fig. 3. – Relationships between the opening pressure ($P_{op}$) and the applied inspiratory threshold pressure ($P_{th}$). $P_{op}$ was measured as the mouth pressure at the beginning of inspiratory flow under each load. The results are shown as mean and ±1SD under several different breathing strategies (different mean inspiratory flow). Each panel represents the results from one subject The dashed line is the line of identity.

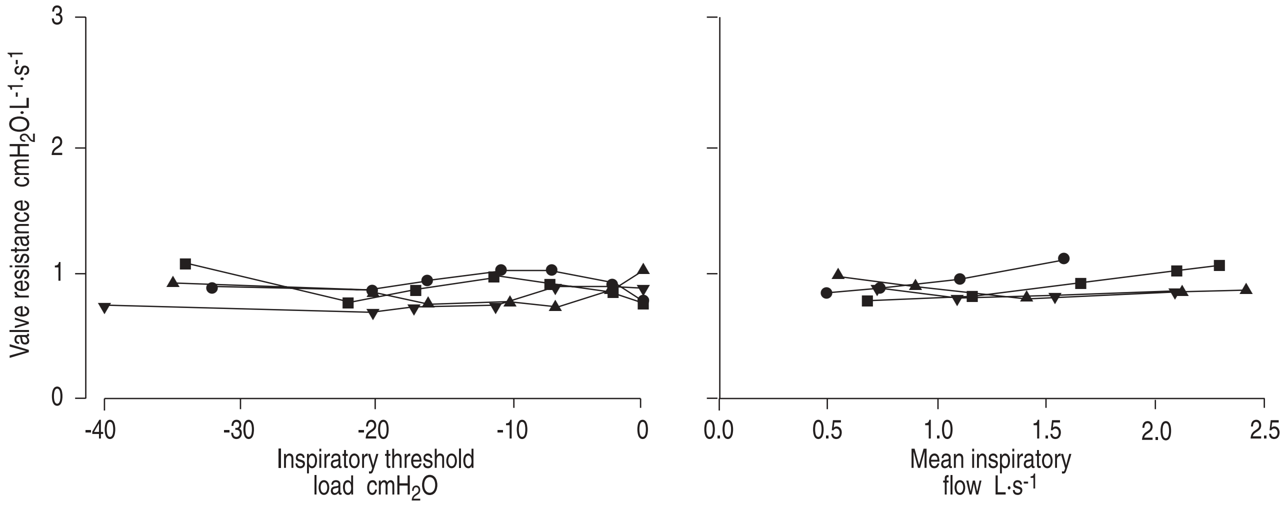


Fig. 4. – Resistance of the inspiratory threshold valve determined during the period of inspiratory flow. Each curve represents the results from one subject.

## Discussion

An ideal inspiratory threshold valve should be able to provide a pure and precise threshold load, such that before the critical pressure is reached, inspiratory flow is absolutely zero and after the critical pressure is reached, the threshold load applied is constant throughout the whole inspiration and independent of the inspiratory flow being generated.

Several different designs of inspiratory threshold valve have been described and used. The spring-loaded valve is the most simple design, but the threshold pressure that it produces is inconsistent, especially in the low flow range [9]. The solenoid inspiratory valve [10] was thought to impose a more accurate load. However, the load from the solenoid valve disappears after initial inspiratory effort and does not last throughout the whole inspiration [10], so that the solenoid valve cannot be considered as an inspiratory threshold load device [11]. The design most commonly used to create an inspiratory threshold load is the weighted plunger, as originally described by NICKERSON and KEENS [7].

In spite of the recent improvement to the design of the inspiratory inlet of the weighted plunger [4, 8], some dependency of the threshold pressure on flow remains [8]. NICKERSON and KEENS [7] proposed that the opening pressure ($P$) of the weighted plunger is determined by the mass of the weight ($M$) and the area of the valve ($A$):

$$P=M\times g/A \quad (1)$$

where $g$ is the gravitational constant. However, equation (1) only describes the pure static condition. When the weighted plunger is lifted dynamically by inspiratory effort, additional force is required to account for the requirements of acceleration. Equation (1) should be rewritten as:

$$P=M\times(g+a)/A \quad (2)$$

where $a$ is the first derivative of the speed of lifting the weighted plunger, which should depend on the speed of the initial inspiratory pressure development. Strictly speaking, the opening pressure of the weighted plunger always includes this element, which is presumably affected by the breathing pattern and, therefore, the weighted plunger does not provide a pure threshold load.

The current set-up fulfils the requirements of an ideal inspiratory threshold load. As demonstrated in figure 2, no flow was generated until the $P_m$ matched the applied $P_{th}$ and the threshold load was applied constantly during the whole inspiration. There are two advantages of the present technique. First, the threshold and opening pressures were measured separately and there was an excellent relationship between them (fig. 3). In the previous set-ups, only $P_{op}$ was measured because of the difficulty in measuring the true $P_{th}$ directly. Secondly, since the pressures on both sides of the inspiratory valve can be measured simultaneously, the flow resistance of the inspiratory threshold valve can be calculated. The resistance was independent of both the mean inspiratory flow and the magnitude of the threshold load (fig. 4), and was not more than the intrinsic resistance of the Hans Rudolph valve and the pneumotachograph. The flow resistance of the weighted plunger has not been reported. Whether or not a threshold valve offers additional resistance should be determined by the mechanism producing the threshold load. The opening of the threshold valve, like the weighted plunger, depends on the pressure gradient established between the atmosphere and the inside of the inspiratory chamber. A certain degree of res-istance at the valve opening is necessary for the mainten-ance of this pressure gradient. It can thus be predicted that the resistance of the weighted plunger would be proportional to the magnitude of the negative pressure gradient for a given flow. For the present system, the opening of the inspiratory valve occurs when the pressure gradient across the valve disappears, so that little additional resistance is produced once flow begins.

With the present set-up, the magnitude and constancy of the inspiratory threshold load depend largely on the characteristics of the flow generator. A major disadvantage of the current set-up is that the maximal reliable inspiratory threshold load is -50 cm$H_2O$. To produce a greater load, a more powerful flow generator is needed. Alternatively, two flow generators arranged in parallel can be connected to the pressure chamber to double the flow and negative pressure outputs. Another disadvantage is that flow generators are usually noisy. It should be noted that al-though the size and shape of the pressure chamber is less important in determining the threshold pressure, the internal diameter of the chamber should not be too small to produce flow resistance within the chamber. The surface area of the pressure chamber must be large enough to allow sufficient holes to be made, so that the negative pressure can be regulated more precisely.

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