J Anesth (2009) 23:93–98
DOI 10.1007/s00540-008-0681-8

Journal of
Anesthesia

A simple, lightweight CPAP-delivery device, composed of a three-way stopcock, for the nondependent lung

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Abstract
Purpose. We aimed to introduce a simple, lightweight continuous positive airway pressure (CPAP)-delivery device for the nondependent lung during one-lung ventilation, to investigate how the type of three-way stopcocks, and the compliance and resistance of a test lung affect the relationship between the oxygen flow rate and CPAP level produced, and to examine how the device works in a clinical setting.
Methods. In the test lung study, the bronchial blocker of a Univent tube was connected to a test lung. The effects of oxygen-flow rate, types of three-way stopcocks, and compliance and resistance of the test lung on the CPAP levels were studied. In the clinical study, the lightweight device was used to treat hypoxia in seven patients during one-lung ventilation with the bronchial blocker.
Results. In the test lung study, the CPAP level produced by the device was proportional to the oxygen-flow rate, dependent on the type of three-way stopcock used, and independent of the compliance or resistance of the test lung. There was no discrepancy between the plateau pressures of the test lung and the monitoring port of an additional stopcock at any degree of compliance or resistance of the test lung at any oxygen-flow rate. Therefore, the relationship between the oxygen-flow rate and CPAP level can be ensured in advance before application to the lung, with an additional three-way stopcock of which the distal end is occluded. In the clinical study, peripheral oxygen sataration (S_{PO_2}) improved while the CPAP level ranged from 2.8 to 5.4 cmH_2O.
Conclusion. The lightweight CPAP delivery-device can provide variable CPAP levels by adjusting the oxygen-flow rate without real-time monitoring of the pressure.

Key words Nondependent lung CPAP · Three-way stopcock · Bronchial blocker

Introduction

One-lung ventilation for thoracic surgery may lead to severe hypoxia, which can be reversed by applying continuous positive airway pressure (CPAP) with 100% oxygen to the nondependent lung. CPAP has been recommended to improve arterial oxygenation [1–4]. Several devices with a pressure gauge or a reservoir bag have been proposed and tested for applying CPAP to the nondependent lung with a bronchial blocker tube [3,5,6]; however, a lighter-weight device without a pressure gauge or a reservoir bag could be dealt with more easily in the clinical setting. We developed a new simple, lightweight CPAP-delivery device that supplies oxygen to the nondependent lung via a three-way stopcock connected to the proximal end of a hollow bronchial blocker tube; the device does not require real-time monitoring of the pressure. Instead of the real-time monitoring, one can accurately measure and ensure the relationship between oxygen-flow rates and CPAP levels in advance of applying the device to the lung. In this study, we tested the effect of several factors (oxygen-flow rate, types of three-way stopcock, and compliance and resistance of the lung) on the CPAP level produced by the new device. We also report relevant clinical data.

Methods

We built our CPAP-delivery device by connecting a three-way stopcock (Connecta Plus 3; Becton Dickinson, Helsingborg, Sweden) to the proximal end of a hollow bronchial blocker. We supplied oxygen to the nondependent lung through the stopcock for pressure relief (Fig. 1A).

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Received: August 16, 2007 / Accepted: August 8, 2008

Test lung study

We tested the device on a test lung (Vent-Aid TTL; Michigan Instruments, Grand Rapids, MI, USA) with a Univent tube of 7.5-mm inner diameter (ID; Univent BB System; Fuji System, Tokyo, Japan) as follows. We connected a bronchial blocker tube to a test lung, and the airway of the test lung was sealed tightly by the inflated cuff of the bronchial blocker tube. We insufflated the tube with oxygen through two three-way stopcocks. Using pressure transducers (model #PX272; Baxter Healthcare, Irvine, CA, USA), we measured pressure at two sites: (1) a pressure-monitoring port (Pmp) between the first three-way stopcock and the hollow bronchial blocker, and (2) the test lung (Pt; Fig. 2, left). The oxygen-flow rate was measured with an electrical flowmeter (NICO; Novametrix Medical Systems, Wallingford, CT, USA) at the oxygen source tube. We recorded the measured pressure and oxygen-flow rate on a personal computer via an analog-to-digital converter (DI200; Dataq Instruments, Akron, OH, USA).

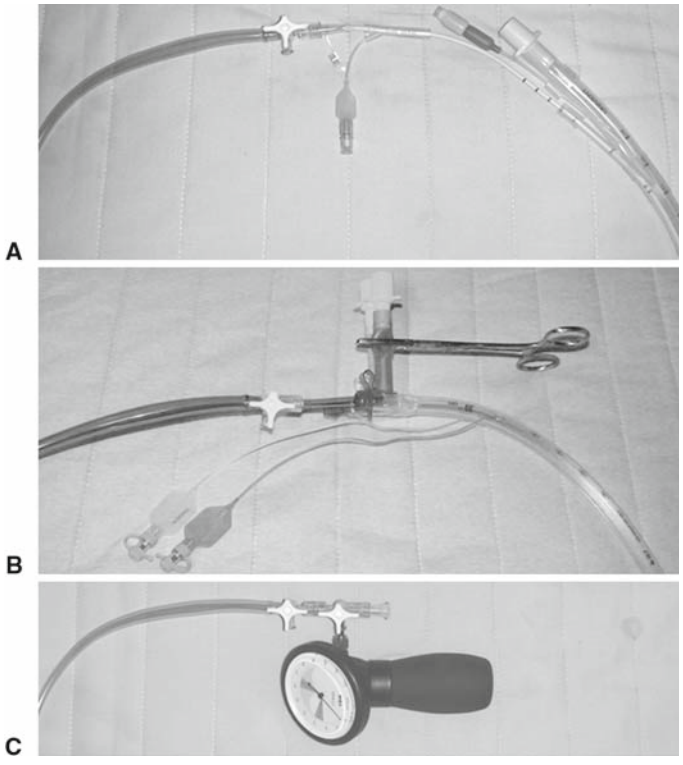

Fig. 1. **A** A simple and lightweight continuous positive airway pressure (CPAP)-delivery device composed of a three-way stopcock between the oxygen tube and the proximal end of the hollow bronchial blocker in the Univent (Fuji System) tube. The open site of the stopcock works as a pressure-relief port. The three-way stopcock is open in all three directions. **B** CPAP-delivery device composed of a three-way stopcock and a funnel-shaped piece of tube tightly connected to the proximal end of the bronchial lumen of a double-lumen tube. **C** The setting to measure the relationship between oxygen-flow rate and CPAP level in advance of using the device. An additional second stopcock attached to a pressure gauge at the end of the port is occluded with a lid

Effects of the oxygen-flow rate and type of three-way stopcock on CPAP levels

To evaluate how the oxygen-flow rate and the type of three-way stopcock affected CPAP levels, we conducted the procedure with three types of stopcock—whose inner-hole diameters were 1.7 mm (A), 1.8 mm (B), and 2.2 mm (C), respectively (A: Terufusion; Terumo, Tokyo, Japan; B: Braun; Nippon Sherwood, Tokyo, Japan; C: Connecta Plus 3; Becton Dickinson)—with a Univent tube. Type C is a default stopcock in the other studies. The compliance of the test lung was set at 50 $ml \cdot cmH_2O^{-1}$, and the oxygen-flow rates were increased by 1-$l \cdot min^{-1}$ increments.

Effects of the compliance and resistance of the test lung on CPAP levels

We set the test lung's compliance at 10, 50, or 150 $ml \cdot cmH_2O^{-1}$ by altering the distance of the spring position from the hinge point of the test lung, and we increased the oxygen-flow rate from 0 $l \cdot min^{-1}$ to 9 $l \cdot min^{-1}$ by 1-$l \cdot min^{-1}$ increments. The oxygen-flow rate was measured with an electrical flowmeter at the oxygen source tube. Furthermore, to evaluate the effect of

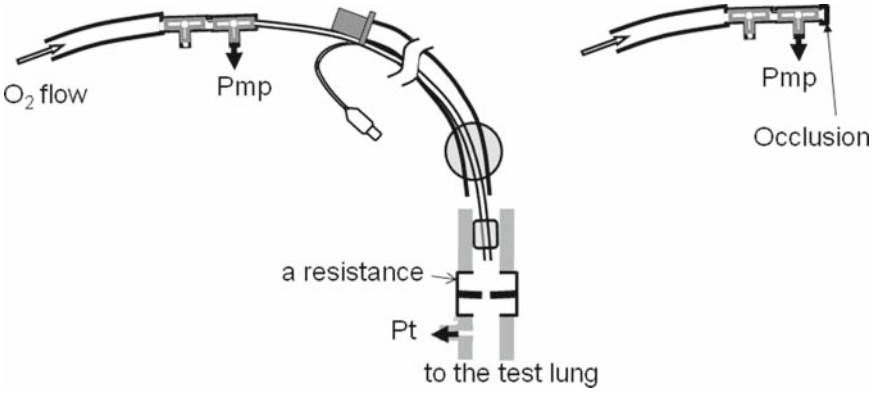

Fig. 2. Schematics of the setting of the test lung study. The CPAP-delivery device with the second three-way stopcock, working as a pressure monitoring port; is connected to the proximal end of the hollow bronchial blocker tube placed in the test lung's airway where the pressure port is and where resistance could be added (*left*). The device with the second stopcock is occluded at the end, and pressure at the monitoring port is measured without the test lung (*right*). *Pmp*, Pressure at the monitoring port; *Pt*, pressure at the test lung

airway resistance on the produced CPAP levels, we added resistance (50 $cmH_2O \cdot l^{-1} \cdot s^{-1}$: #13394-03 Pneuflo Resistor; Michigan Instruments, Grand Rapids, MI, USA) in the test lung's airway (Fig. 2, left).

Without the test lung, we occluded the distal end of the second three-way stopcock and measured the pressure at the pressure-monitoring port (Pmp) while the oxygen-flow rate was increased from 0 $l \cdot min^{-1}$ to 9 $l \cdot min^{-1}$ in 1-$l \cdot min^{-1}$ increments (Fig. 2, right), to determine whether we could measure and ensure the relationship between oxygen-flow rate and CPAP using a pressure gauge (Cuff Pressure Gauges, 54-07-000; VBM, Medizintechnik, Sulz aN, Germany) through an additional stopcock whose distal end was occluded (Fig. 1C) in advance of applying it to the lung.

Effect of the device on the double-lumen tube

The same procedure as that used for the Univent tube was conducted with a 39-Fr left-sided double-lumen tube (Blue line endobronchial tube; Portex, Keene, NH, USA), with the proximal end of the endobronchial lumen connected to the stopcock with a connection tube that was a piece of oxygen supply tube whose inner diameter ranged from 3.2 mm to 7.9 mm (Green bubble tube; Nippon Sherwood, Tokyo, Japan; Fig. 1B). To prevent the leakage of gas, a funnel-shaped piece of oxygen supply tube was inserted tightly into the proximal end of the endobronchial lumen.

We repeated the procedure four times and determined the average values in each condition.

Statistical analysis

The differences in the effects of the type of three-way stopcock, different places of pressure-monitoring ports, and resistance and compliance of the test lung were evaluated by a two-way analysis of variance (oxygen-flow rate × type of three-way stopcock, oxygen-flow rate × type of port, oxygen-flow rate × type of resistance, or oxygen-flow rate × type of compliance). *P* values of less than 0.05 were considered to indicate statistical significance.

Clinical study

After obtaining Institutional Research Board approval and informed consent, we compared peripheral oxygen saturation (Sp_{O_2}) before and after delivering CPAP with our device. Forty-five patients (American Society of Anesthesiologists physical status classification I or II) who required one-lung ventilation during surgery were anesthetized without premedication. We induced anesthesia with propofol 1.5–2.5 $mg \cdot kg^{-1}$ and maintained the airway with a Univent BB System (Fuji System) or an Endobronchial Blocker Tube (Coopdech, Osaka, Japan). Tracheal intubation was assisted with fentanyl 1–2 $\mu g \cdot kg^{-1}$ and vecuronium 0.1–0.2 $mg \cdot kg^{-1}$. Anesthesia was maintained with sevoflurane and epidural anesthesia with infusion of 0.375% ropivacaine. At the anesthetist's discretion, we gave fentanyl in increments of 25–50 μg i.v.

If the oxygen saturation, measured by pulse oximetry (Sp_{O_2}), dropped below 96%, even while ventilating the dependent lung with 100% oxygen, after confirming that the bronchial blocker's balloon was properly positioned with bronchoscopy, we applied the CPAP device. First, we blocked the pressure-relief port of the stopcock with a finger, insufflating oxygen into the depleted nondependent lung until the lung was inflated to below approximately one-fifth of its full capacity, estimated visually (partial recruitment maneuver). We set the oxygen-flow rate at 4 $l \cdot min^{-1}$, which produced a CPAP of 2.8 cmH_2O in the steady state. Then, if oxygenation did not improve, we conducted the partial recruitment maneuver again and increased the oxygen-flow rate by 1-$l \cdot min^{-1}$ increments. For each patient, before applying the CPAP-delivery device, to confirm the relationship between oxygen-flow rates and CPAP levels, we measured the pressure at the pressure-monitoring port (Pmp) as the oxygen-flow rate was set at 3, 4, 5, 6, and 7 $l \cdot min^{-1}$, while the distal end of the second three-way stopcock was occluded (Fig. 1C).

Statistical analysis

We used Student's *t*-test to evaluate the effects of the CPAP device on Sp_{O_2}. Data values are presented as means ± SD. A *P* value of less than 0.05 was considered to indicate statistical significance.

Results

Test lung study

Effects of the oxygen-flow rate and type of three-way stopcock on CPAP levels

The CPAP level and the plateau pressure of Pt were proportional to the oxygen-flow rate. The CPAP level was dependent on the type of three-way stopcock; stopcock type C, which had the largest ID holes, showed the lowest pressure at all oxygen-flow rates (Fig. 3).

Effects of the compliance and resistance of the test lung on CPAP levels

The CPAP level was proportional to the oxygen-flow rate, and the relationship did not differ among the different lung compliances or airway resistances with the Univent tube (Fig. 4D, E). There was no discrepancy between the plateau pressures at the test lung and at the monitoring port with the additional stopcock (Fig. 4A, D and B, E). The values of the plateau pressure of Pmp

when the distal end of the second three-way stopcock was occluded did not differ according to the values of the plateau pressures of Pt or Pmp in regard to any degree of compliance or resistance of the test lung at each oxygen-flow rate (Fig.4A–E).

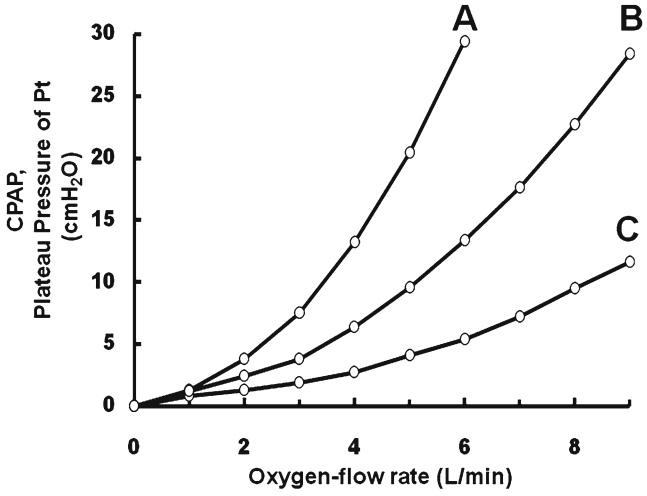

Fig. 3. CPAP (plateau pressure of Pt) levels of each tested three-way stopcock (types *A*, *B*, and *C*; see the "Methods" section in the text). The plateau pressures were produced by various oxygen-flow rates in the test lung that had compliance of 50 ml·cmH_2O^{-1}

Effect of the device on the double-lumen tube

The same relationships between oxygen-flow rate and produced CPAP level as those obtained for the Univent tube were obtained with the lightweight CPAP-delivery device connected to the bronchial lumen of the double-lumen tube.

Clinical study

The Pmps produced at oxygen-flow rates of 3, 4, 5, 6, and 7 l·min^{-1}, which were measured in advance of connecting the device to the blocker tube, were equal to the Pmps in the corresponding curve in Fig. 4C. Seven of the 45 subjects (age, 62.5 ± 13.5 years; five men and two women) showed S_{pO_2} of less than 96% during one-lung ventilation, and the device was applied to treat the hypoxia. The applied oxygen-flow rate ranged from 4 to 6 l·min^{-1} (CPAP, 2.8 to 5.4 cmH_2O) to improve oxygenation. S_{pO_2} improved from 92.6 ± 1.6 % to 98.2 ± 0.9 % ($P < 0.05$). The partially inflated nondependent lung with the CPAP did not interfere with the surgical procedure.

Discussion

The present study demonstrated that: (1) the values of the plateau pressure of Pmp when the distal end of the

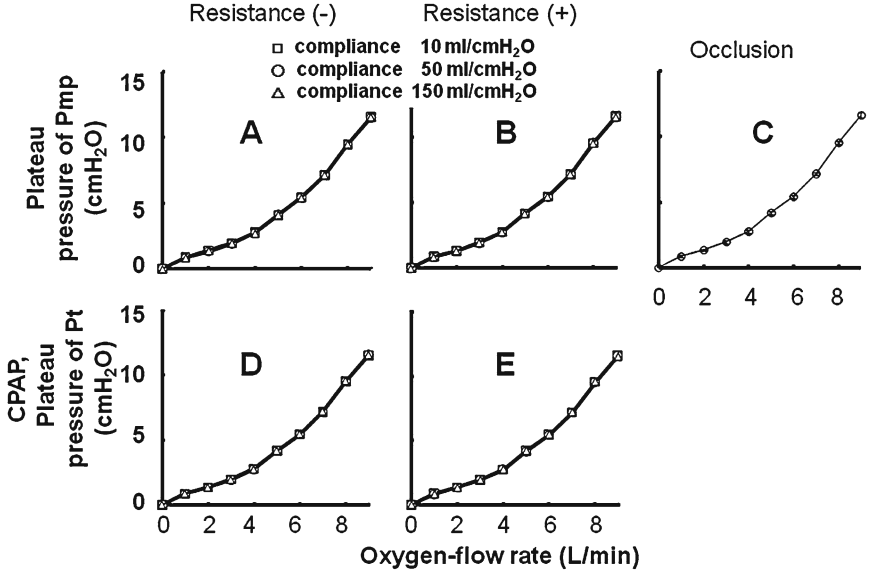

Fig. 4A–E. **A** The relationship between the plateau pressure of the pressure at the monitoring port (*Pmp*) and the oxygen-flow rate at three compliances (10 [*squares*], 50 [*circles*], and 150 [*triangles*] ml·cmH_2O^{-1}) of the test lung without resistance in the airway of the test lung. **B** The relationship between the plateau pressure of Pmp and the oxygen-flow rate at three compliances with resistance (50 cmH_2O·l^{-1}·s^{-1}) added to the airway of the test lung. **C** The relationship between the plateau pressure of Pmp and the oxygen-flow rate with occlusion at the end of the second three-way stopcock (*Fig. 2, right*). **D** The relationship between CPAP (plateau pressure of Pt) and the oxygen-flow rate at three compliances without resistance. **E** The relationship between CPAP (plateau pressure of Pt) and the oxygen-flow rate at three compliances with resistance. In **A**, **B**, **D**, and **E**, the three lines produced at each of the three compliances (10 [*squares*], 50 [*circles*], and 150 [*triangles*] ml·cmH_2O^{-1}) overlap each other

second three-way stopcock was occluded without the test lung were similar to the values of the plateau pressures of Pt or Pmp at any degree of compliance or resistance of the test lung at each oxygen-flow rate (Fig. 4), (2) the CPAP delivery device can reliably provide variable CPAP levels by altering the rate of oxygen flow even without real-time monitoring of the pressure, because the relationship between the oxygen-flow rate and CPAP level can be measured and ensured in advance of applying the device to the lung, by using a pressure gauge connected through the additional second three-way stopcock, (3) the CPAP level was dependent on the type of three-way stopcock (Fig. 3), and (4) the device can be used with a double-lumen tube as well as with a Univent tube.

Although the basic elements of our device seem to be similar to those previously described [5], in which the CPAP delivered was dependent on the oxygen-flow rate, our device has two advantages. First, one can easily ensure the relationship between the oxygen-flow rate and the produced CPAP at each oxygen-flow rate by using a pressure gauge via an additional second three-way stopcock connected to the distal end of the stopcock of the device and occluded at the end (Fig. 1C) in advance of applying the device to the patient's lung. That the compliance and the resistance do not affect the relationship between the oxygen-flow rate and CPAP allows us to use the device without real-time monitoring of the pressure by a pressure gauge or a reservoir bag. A second advantage is the easy handling induced by the lightweight nature of this setup, which is vital for clinical use because heavy devices would be difficult to hold up and would tend to induce accidental malpositioning of the bronchial blocker, resulting in the disturbance of one-lung ventilation. These advantages are gained by the differences in the alignment of the stopcocks for the pressure monitoring port of our device (Fig. 5A) from that of the device [5] whose alignment is shown in Fig. 5B. In alignment B, the pressure monitoring port is in the way of the gas-flow at equilibrium, and the alignment inevitably leads to a discrepancy between the plateau pressure of Pmp and Pt even at equilibrium (Fig. 6, right). On the other hand, in our device, the pressure monitoring port is out of the way of the gas-flow at equilibrium, and the alignment does not lead to this discrepancy (Fig. 6, left).

Nondependent-lung CPAP should be applied during the deflation phase of a large tidal-volume breath to overcome critical opening pressures in the atelectatic lung (3). Jet ventilation through the bronchial blocker lumen could be applied to provide a tidal volume before attaching the CPAP system [5], but instead of using jet ventilation we insufflated oxygen to the nondependent

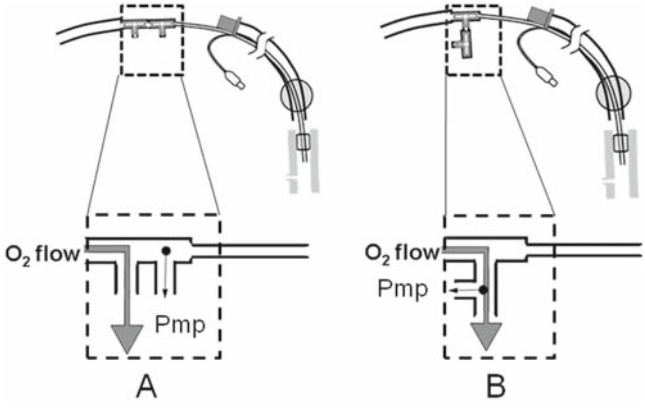

Fig. 5A,B. Two alignments of three-way stopcocks for the monitoring port. **A** The monitoring port is out of the way of the remaining gas flow at equilibrium. **B** The monitoring port is in the way of the remaining gas flow at equilibrium. *Large gray arrows* indicate the gas flow at equilibrium

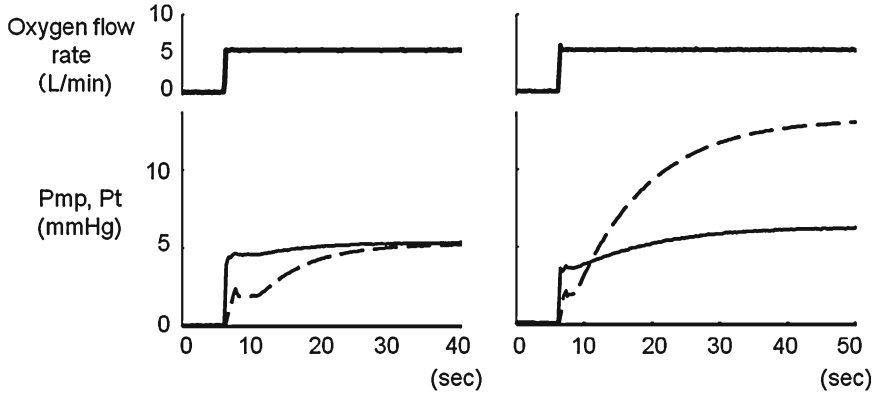

Fig. 6. Different effects of the two alignments of the three-way stopcocks shown in Fig. 5 on the time course of the pressure of the monitoring port (*Pmp*) and the pressure of the test lung (*Pt*) at an oxygen-flow rate of 5 $l \cdot min^{-1}$ with compliance of the test lung set at 50 $ml \cdot cmH_2O^{-1}$. Pt is shown with a *dotted line*. Pmp is shown with a *solid line*. *Left*, the plateau pressure of Pmp is equal to the plateau pressure of Pt in the time course of the pressures of alignment A in Fig. 5**A**; the plateau pressure of Pt is greater than the plateau pressure of Pmp in the time course of pressures of alignment B in Fig. 5**B**

lung until the lung was inflated to approximately one-fifth of the fully inflated volume, estimated visually by manually blocking the pressure relief port at the three-way stopcock of the device using a finger, under direct and close observation of the lung.

Figure 3 shows that when we used stopcock type A (whose inner-hole diameter is smaller than that of type C) in the device, we were able to reduce the oxygen-flow rate of the CPAP-delivery device. Such a reduction may be beneficial to cut costs; however, a more precise adjustment of oxygen-flow rate may be required.

Our proposed device has two limitations. First, even if we can measure the airway pressure of the nondependent lung at equilibrium at each oxygen-flow rate in advance, until equilibrium is achieved, a discrepancy exists between the pressure of the test lung (Pt) and the pressure at the monitoring port (Pmp), as shown on the left in Fig. 6. Second, theoretically, the plateau pressure at the monitoring port should be slightly lower than that at the actual lung's airway because of the slight oxygen flow that continues in the hollow bronchial blocker even at equilibrium, due to oxygen absorption in the nondependent lung.

In conclusion, we developed and evaluated a new simple, lightweight CPAP-delivery device, composed of an oxygen source and a three-way stopcock, for one-lung ventilation. Adjusting the oxygen-flow rate, one can deliver variable and stable CPAP regardless of the nondependent lung's compliance and resistance, while the CPAP level is dependent on the type of three-way stopcock used. In the clinical trial, we successfully used the device to treat hypoxia caused by one-lung ventilation, without disturbing the surgical procedure. This device may be useful in the clinical setting.

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