Preliminary development and evaluation of the support system for care of mechanically ventilated patients

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Editor’s key points

- It is sometimes difficult to quickly identify the source of a leak in a ventilator circuit, and delays may lead to patient harm.
- Training and performance of nurses caring for mechanically ventilated patients varies substantially.
- This study used an integrated multi-sensor with visual display to enhance detection and correction of the source of circuit leak or disconnection.

Background. We wanted to demonstrate the feasibility of a novel computer-assisted ventilator alarm system, the support system for care of mechanically ventilated patients (SCMVP), to detect gas leaks and provide graphical information on the site of the leak in a manikin model.

Methods. We tested six leakage scenarios. Four scenarios were applied to both the respiratory circuits with the SCMVP and without the SCMVP (conventional system), and two scenarios were each specific to one of the systems. Fifteen registered nurses were asked to manage three scenarios each (two mutual and one system-specific scenario). Time to identify the site of the leak was measured and compared between the two systems.

Results. The SCMVP showed significantly shorter time for troubleshooting in one of the four mutual scenarios and shorter accumulated time for troubleshooting in the four mutual scenarios [18.0 (range, 14.5–19.5) and 48.5 (9.0–180.0) s, respectively] compared with the conventional system [76.0 (47.0–133.8) and 82.5 (16.0–180.0) s, respectively]. In the mutual scenarios, SCMVP resulted in significantly more frequent incidences of successful troubleshooting within 30 s and less frequent incidences of troubleshooting requiring >180 s [43.3% (13/30) and 6.7% (2/30), respectively] compared with the conventional system [13.3% (4/30) and 30% (9/30), respectively].

Conclusions. The SCMVP can facilitate rapid and successful recognition of the site of leak in a respiratory circuit in a simulation environment.

Keywords: monitoring, ventilation; safety, equipment

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Care of mechanically ventilated patients requires a high degree of medical resources and healthcare providers who possess knowledge of ventilator use. The Japan Council of Quality Health Care reported that more than 100 medical near-miss/adverse events occurred in 1 yr in mechanically ventilated patients.1 Leaks in the respiratory circuit are one potential cause of these events. Inadequate ventilation caused by a major leak, such as disconnection of the circuit, dislodgement of the tracheal tube, or equipment malfunction, may result in serious patient harm. Although prompt troubleshooting is highly desirable, it is not always easy to identify the origin of the leak.2,3 In this near-crisis situation, the healthcare provider has to identify the cause of the leak during a time of heavy workload (e.g. closely observing the patient, securing a backup means of ventilation, or calling for assistance). Staff performance is variable and dependent on individual training and competence. We thus wanted to develop a better support system for care of mechanically ventilated patients (SCMVP).

The primary design goal of the SCMVP was to provide both clear recognition of, and graphical information on, the site of the leak in the respiratory circuit. The SCMVP consists of five components comprising a multi-sensor package for the respiratory circuit, a respiratory circuit disconnection detection system, a display panel, a respiratory circuit support arm with built-in signal transmission cabling system, and a warming holder for a heat-moisture exchanger. We sought to test our hypothesis that providing graphical information of the site of a respirator-related problem on a display would improve the healthcare provider’s ability to identify the site of a leak in a simulation environment. In this pilot study, we evaluated the impact of the SCMVP prototype on the time required to
troubleshoot a respiratory circuit leak in simulated near-miss/adverse events using a mechanically ventilated manikin.

**Methods**

The Institutional Review Board of Teikyo University, School of Medicine, University Hospital Mizonokuchi approved this study as an exempt study. Written informed consent was obtained from all participants in the study.

**SCMVP components**

**Component 1**

This is a multi-sensor package for the respiratory circuit (Fig. 1). The gas flow sensor, carbon dioxide (CO2) detection sensor, and pressure sensor are integrated into a respiratory multi-sensor package. The gas flow sensor uses a bidirectional measurement system using ultrasound with temperature correction. The measurement range is from $250$ to $50$ litre min$^{-1}$, and the response speed is 2 ms. CO2 is monitored by a solid electrolyte-type sensor with a measurement range of 350–10 000 ppm and a response speed of 90 s. The pressure sensor is a small, on-board sensor with a measurement range from 0 to 100 cm H2O and a response speed of 1 ms. The multi-sensor package weighs 250 g with a dead space volume of 10 ml. The information collected by the respiratory multi-monitor package is continuously analysed by the micro-computer of the SCMVP (Appendix).

**Component 2**

This is a respiratory circuit disconnection detection system (Fig. 1). To detect disconnections, the SCMVP has a sensor unit at the connection between the respiratory circuit and the inspiratory and expiratory outlets of the ventilator. It has a white light-emitting diode and colour-coded sensor that receives reflected light from a tape covering the end of the respiratory circuit to monitor the connection condition. It prevents not only disconnection but also poor connection.

**Component 3**

This is a display panel for the integrated information system (Fig. 1, Table 1). Information on problems including the site of the leak is visually and clearly displayed on an 11 in screen according to the processed signals received from the sensors.

**Component 4**

This is a respiratory circuit support arm with built-in signal transmission cabling system (Fig. 1). This newly developed stainless steel respiratory circuit support arm allows passage inside the arm of the cables that transmit the signals from the respiratory multi-sensor package.

**Component 5**

This is a warming holder for a heat-moisture exchanger (Fig. 1). A heat-moisture exchanger was adopted in the SCMVP. Although it is well known that an active humidification system is more effective than a heat-moisture exchanger, such a system requires routine checks of water level or clearing of water accumulated in the respiratory circuit. Further, the complicated connection between circuits could be a potential cause of an air leak that is often hard to identify. The SCMVP includes a holder for a heat-moisture exchanger with warming function for enhanced humidification that allows for easy care.

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Fig 1  (A) Photograph of the prototype support system for care of mechanically ventilated patients (SCMVP). (B) Schematic illustration of the SCMVP components. Component 1: multi-sensor package for the respiratory circuit. Component 2: respiratory circuit disconnection detection system. Component 3: display panel for the integrated information system. Component 4: respiratory circuit support arm with built-in signal transmission cabling system. Component 5: warming holder for a passive humidification system.
Table 1  Screen display, status messages, comments, and definitions of abnormality of the SCMVP. SCMVP, support system for care of mechanically ventilated patients

<table>
<thead>
<tr>
<th>Panel</th>
<th>Screen display</th>
<th>Possible status</th>
<th>Comment on display</th>
<th>Definition of abnormality</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td><img src="image1" alt="Screen display" /></td>
<td>Normal status</td>
<td>Normal condition</td>
<td>No abnormality detected</td>
</tr>
<tr>
<td>b</td>
<td><img src="image2" alt="Screen display" /></td>
<td>Disconnection or loose connection at the inspiratory outlet</td>
<td>Check the connection at the inspiratory outlet</td>
<td>Colour-coded sensor cannot detect reflected light from a tape covering the end of the inspiratory limb of the circuit</td>
</tr>
<tr>
<td>c</td>
<td><img src="image3" alt="Screen display" /></td>
<td>Disconnection or loose connection at the expiratory outlet</td>
<td>Check the connection at the expiratory outlet</td>
<td>Colour-coded sensor cannot detect reflected light from a tape covering the end of the expiratory limb of the circuit</td>
</tr>
<tr>
<td>d</td>
<td><img src="image4" alt="Screen display" /></td>
<td>Major air leak occurring between tracheal tube and multi-sensor package or around tracheal tube</td>
<td>Check for disconnection at tracheal tube, or check for air leak around tracheal tube</td>
<td>Multi-sensor package detects a decrease in expired tidal volume to &lt; 50% of the mean delivered tidal volume of the 3 prior consecutive breaths</td>
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Table 1 Continued

<table>
<thead>
<tr>
<th>Panel</th>
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<th>Possible status</th>
<th>Comment on display</th>
<th>Definition of abnormality</th>
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<tbody>
<tr>
<td>e</td>
<td><img src="image1.png" alt="Screen display image" /></td>
<td>Major air leak occurring between multi-sensor package and the outlet</td>
<td>Check for disconnection along the circuit between the multi-sensor package and the outlets</td>
<td>Multi-sensor package detects a decrease in delivered tidal volume to &lt;50% of the mean expiratory tidal volume of the 3 prior consecutive breaths</td>
</tr>
<tr>
<td>f</td>
<td><img src="image2.png" alt="Screen display image" /></td>
<td>Disconnection of tracheal tube, oesophageal intubation, or disruption of ventilation</td>
<td>Check for disconnection at tracheal tube, or check for air leak around tracheal tube</td>
<td>Multi-sensor package detects a pause in expiration of CO(_2) for &gt;90 s</td>
</tr>
<tr>
<td>g</td>
<td><img src="image3.png" alt="Screen display image" /></td>
<td>Obstruction of circuit</td>
<td>High intra-circuit pressure. Check for potential tracheal tube obstruction, clogging of heat-humidity exchanger, or expiratory valve malfunction</td>
<td>Multi-sensor package detects that maximal airway pressure exceeds 35 cm H(_2)O in 2 consecutive breaths</td>
</tr>
</tbody>
</table>

Display patterns for normal and abnormal status

The SCMVP displays screens for seven patterns of problems including one screen displaying normal status (Table 1, panel a). Table 1 illustrates the screen displays, possible status, and comment shown on the screen display, and defines the abnormalities. When the colour-coded sensor loses light reflected from a tape covering the end of the inspiratory or expiratory outlet, the SCMVP issues an alert indicating a disconnection or loose connection at the inspiratory or expiratory outlet (Table 1, panels b and c). We utilized changes in the delivered and expired tidal volume derived from the respiratory flow to detect air leaks and to estimate the location of the leak. The threshold of change in the tidal volume was set to detect a major air leak. We defined a decrease in the expired tidal volume to <50% of the mean tidal volume delivered in the 3 prior consecutive breaths as indicating a major air leak occurring between the tracheal tube and multi-sensor package or around the tracheal tube (Table 1, panel d). Additionally, we defined a decrease in delivered tidal volume to <50% of the mean expiratory tidal volume in the 3 prior consecutive breaths as indicating a major air leak occurring between the multi-sensor package and the outlet (Table 1, panel e).
A pause in the detection of expired CO₂ of more than 90 s was defined as a problem associated with the tracheal tube (Table 1, panel f). Clinically, a sustained loss of CO₂ detection during mechanical ventilation could mean disconnection or malposition of the tracheal tube including unplanned tracheal extubation. This alert may overlap with the case of major leak between the tracheal tube and multi-sensor package or around the tracheal tube (panel d). However, panel f would be specifically activated when the expired tidal volume was maintained at more than 50% of delivered volume while expired CO₂ was not detected, for example, oesophageal intubation with partial return (more than 50% of volume) of insufflated air from the ventilator, or a mistake in reconnecting the ventilator circuit to the patient after tracheal suction while the ventilator continued working with a test lung. To detect an obstruction occurring at any point within the respiratory circuit, we defined an intra-circuit high pressure exceeding 35 cm H₂O in 2 consecutive breaths as indicating a problem for which a notification should be displayed on the monitor screen (Table 1, panel g).

Simulation study methods

Fifteen registered nurses participated in this study. They were not certified as critical care nurses, but they all had experience in providing care to mechanically ventilated patients. Care was simulated using a manikin (Deluxe Difficult Airway Trainer; Laerdal Japan, Tokyo, Japan) with a conventional respiratory circuit (conventional system) or a respiratory circuit supported by the SCMVP (SCMVP). The trachea of the manikin was intubated with a tracheal tube with a standard 7 mm cuff that was fixed at the 23 cm mark of the tube using a tube holder (Thomas™ Endotracheal Tube Holder; Laerdal Japan). Intra-cuff pressure was controlled at 20 cm H₂O. The respiratory circuit was connected to the tracheal tube using a rotary connector with a short flexible tube (F&P connector; Fisher & Paykel Healthcare KK, Tokyo, Japan). The manikin’s lungs were mechanically ventilated by a Newport E500 ventilator (Newport Medical Instruments, Costa Mesa, CA, USA) with a tidal volume of 500 ml and a respiratory rate of 10 bpm. Simultaneously, CO₂ was insufflated at 0.1 ml min⁻¹ into the distal lung to maintain end-tidal CO₂ at 40 (10) mm Hg on capnography. To provide humidity, an active humidification system was installed in the respiratory circuit of the conventional system (MR850 Humidifier; Fisher & Paykel Health Care KK), and a heat-moisture exchanger (DAR Hygrobac; Covidien Japan, Tokyo, Japan) was installed in the respiratory circuit of the SCMVP.

The participants underwent a short technical briefing on the SCMVP before the study. Other than the ventilator and breathing circuits, only a cuff pressure manometer, a syringe for cuff insufflation, and a stethoscope were available. Before entering the study room, the leak condition was already in effect. The participants were told only that a manikin simulating a mechanically ventilated patient was on the bed and that they were to identify the site of the problem as quickly as possible. When they entered the study room, the alarm system of the ventilator was already activated with the conventional system, whereas both the alarm systems of the ventilator and the SCMVP were already activated with the SCMVP.

On the basis of The Japan Council of Quality Health Care report, we developed medical near-miss/adverse event scenarios simulating typical leaks in the respiratory circuit as follows, with the associated screen display indicated in Table 1. Scenario 1: leak at the tracheal tube cuff caused by inadequate cuff pressure (Table 1, panel f); scenario 2: disconnection of the respiratory circuit at the connection between the tracheal tube and the rotary connector (Table 1, panel d); scenario 3: disconnection of the respiratory circuit at the Y-connector (Table 1, panel e); scenario 4: unplanned extubation (Table 1, panel f); scenario 5, for the SCMVP only: disconnection of the respiratory circuit at the inlet of the respirator (Table 1, panel b); and scenario 6, for the conventional system only to compare with scenario 5: disconnection of the respiratory circuit at the inlet of the MR850 humidifier (Table 1, panel e). Scenarios 1–4 were applicable to both systems, and scenarios 5 and 6 were each specific to one of the two systems. For evaluation of each study participant, we randomly assigned two scenarios from scenarios 1–4 to the conventional system and the other two scenarios to the SCMVP. Scenario 5 was assigned to the SCMVP and scenario 6 was assigned to the conventional system for all participants. Thus, each participant was to handle six scenarios in total, starting with three scenarios assigned to one of the two systems followed by another three scenarios assigned to the other system. The order of system assignment was selected randomly.

We measured the time from the participant entering the room until the site of the leak was identified as the troubleshooting time, which was compared between the two systems in scenarios 1–4. Troubleshooting time in scenarios 1–4 was accumulated and compared between the two systems, and a troubleshooting time of >180 s was deemed failure to troubleshoot. We also measured the incidence of successful troubleshooting within 30 s. The incidence of troubleshooting within 30 s or that of failure to troubleshoot for scenarios 1–4 was compared between the two systems.

The participants were working in hospital departments different from the investigators. The results of the evaluation were stored confidentially by one of the investigators and never disclosed to anyone. The data for statistical analysis were obtained in an anonymous manner; therefore, the participants were free from fear of any consequences caused by low performance in the study.

Statistical analysis

Data are presented as the median and range. Data for troubleshooting time were compared using the Wilcoxon signed-rank test. The incidences of successful troubleshooting within 30 s or failure to troubleshoot were compared using Fisher’s exact test. According to our preliminary study, a prospective power analysis at 80% power and a two-tailed, 0.05 level of significance showed that at least 15 operators would be adequate
to detect a difference of a 33% shortening of troubleshooting time. A value of $P<0.05$ was considered statistically significant.

**Results**

A total of 15 registered nurses were recruited, and all consented to participate in the study (Fig. 2). Their median experience in clinical practice was 10 (3–23) yr including respiratory care with mechanical ventilators. There was no significant difference in the duration of experience of participants between the assigned systems. There were 45 scenarios evaluated with each system. The SCMVP was appropriately activated to graphically indicate the site of the respiratory circuit leak in all evaluations.

Troubleshooting times for scenarios 1–4 are shown in Figure 3. In scenario 2, troubleshooting time was 18.0 (14.5–19.5) s with the SCMVP, which was significantly shorter than that with the conventional system of 76.0 (47.0–133.8) s ($P<0.01$). The accumulated time for troubleshooting was 48.5 (9.0–180.0) s for the SCMVP and 82.5 (16.0–180.0) s for the conventional system. The accumulated time for troubleshooting with the SCMVP was also significantly shorter than that with the conventional system ($P<0.05$). However, other values did not differ significantly between the two systems.

For scenarios 1–4, the incidences of troubleshooting within 30 s and failure to troubleshoot are shown in Table 2. The incidence of quick troubleshooting was significantly higher for the SCMVP than for the conventional system, whereas the incidence of failure to troubleshoot was significantly lower for the SCMVP than that for the conventional system. The SCMVP contributed to both faster and more successful troubleshooting compared with the conventional system.

Troubleshooting time was 19 (9–35) s in scenario 5 (specific to the SCMVP) and 172 (26–180) s in scenario 6 (specific to the conventional system). When compared with each other, troubleshooting time was much shorter for scenario 5 than for scenario 6 ($P<0.001$). For scenario 5, no participants experienced failure to troubleshoot, and 13 of 15 participants
identified the site of the leak within 30 s. For scenario 6, six of 15 participants experienced failure to troubleshoot, and only one participant completed the task within 30 s.

**Discussion**

In the present study, we found that the SCMVP decreased the troubleshooting time and improved the success rate to identify simulated leaks during mechanical ventilation using a manikin.

There is a growing body of evidence to suggest that increased workload might negatively affect patient outcomes such as those of mortality, healthcare-associated infection, postoperative complications, and drug-related adverse events. Severity of the background illness of mechanically ventilated patients demands frequent observation and measurement, multiple routine nursing treatments, and coincidental operational checks of the life-support apparatus. When ventilator-related problems occur, healthcare providers try to fix such problems at a time of great stress. In this near-crisis situation, the healthcare provider has to identify the cause of the leak during a time of heavy workload (e.g. closely observing the patient, securing a backup means of ventilation, or calling for assistance). Procedures to examine the respiratory circuit are variable and depend on the individual nurse. It is an empirical fact that these challenging situations increase the psychological stress and workload of the providers. However, troubleshooting associated with respirators usually depends on the individual skill and insight of the healthcare provider because alarms installed in respiratory ventilators are designed to simply attract attention and give primary information on the type of abnormality but not on the site of the problem.

Previously, several studies evaluated the usefulness of alarm algorithms using pictorial display formats for breathing circuits, whose concept was similar to that of the SCMVP. These intelligent alarm systems provided automatic differential diagnosis of faults with significant reliability and the presentation of graphical information by these systems provided shorter response time for anaesthesiologists to identify critical events during simulated general anaesthesia. In our study, the SCMVP accelerated and facilitated identification of leaks, presumably due to the automatically diagnosed graphical information indicating the site of the leak displayed on the

**Table 2** Incidences of troubleshooting by time in scenarios 1–4. SCMVP, support system for care of mechanically ventilated patients. **P<0.01, *P<0.05, compared with the conventional system**

<table>
<thead>
<tr>
<th></th>
<th>Conventional system</th>
<th>SCMVP</th>
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<tbody>
<tr>
<td>Incidences of troubleshooting</td>
<td>&lt;30 s</td>
<td>30–180 s</td>
</tr>
<tr>
<td>Conventional system</td>
<td>4</td>
<td>17</td>
</tr>
<tr>
<td>SCMVP</td>
<td>13**</td>
<td>15</td>
</tr>
</tbody>
</table>

**Fig 3** Troubleshooting times for scenarios 1–4 and accumulated time for these mutual scenarios. The bold horizontal bar, the boxes, and the whiskeys represent the median value, inter-quartile range, and 10th–90th percentile range, respectively. SCMVP, support system for care of mechanically ventilated patients. **P<0.01, *P<0.05, compared with the conventional system.**
monitor, which was consistent with the previous studies.\textsuperscript{10, 11} However, our study used nurses during simulated mechanical ventilation and not anaesthesiologists during simulated general anaesthesia. Moreover, even though the systems reported in the previous studies were effective and sophisticated, none of these systems is available in the market even after two decades. We assumed that these systems would also be experimental, profuse, respirator-specific, and expensive for routine practice. We are developing the SCMVP for the purpose of commercialization because technical advancements have enabled drastic downsizing and reduced cost of the equipment needed to meet the requirement for practical use. Additionally, a wide variety of respirators have been distributed worldwide, and from the economical point of view, it may be hard to upgrade multiple alarm system software for each model of respirator. However, the SCMVP is an adjunctive system that is compatible with any type of respirator and was designed to work in parallel with the respirator’s built-in alarm system. Therefore, it can provide increased patient safety with minimal additional investment.

In our scenarios, we assigned 3 min as the cut-off time for troubleshooting to compare durations required to identify the site of a leak. In clinical situations, however, patients would usually be disconnected from the leaking respiratory circuit and manually ventilated within a much shorter time than 3 min. Even though patient safety would be secured with this procedure, detection of the leak would continue and would cost time and add to the workload of the nursing team until it was resolved. Results of the present study suggest the possibility that the SCMVP may reduce the time and workload required to discover the site of the leak. Our results from scenarios 5 and 6 showed that the disconnection detection system at the outlets of the ventilator worked well and that leaks at the active humidification system were hard to identify. The latter finding is in accordance with medical near-miss/adverse events reported previously in Japan.\textsuperscript{1} We replaced the active humidification system with a heat-moisture exchanger in the SCMVP prototype to reduce the number of adverse events related to humidification in addition to the technical reason of avoiding interference of the gas flow sensor by humidity.

This was a manikin-based study rather than a clinical study. A manikin cannot fully reproduce conditions seen in mechanically ventilated patients. For example, the direction, rate, or velocity of the intra-circuit flow was relatively simple during this study. However, the combined pattern of these parameters in the clinical situation will be much more complex due to spontaneous breathing, breath holding, bucking, body movement, or tracheal suction. Although the SCMVP successfully detected leaks, provided automatic differential diagnosis of faults, and activated the appropriate monitor display in all 45 evaluations, the number of evaluations was significantly limited for assessment of sensitivity and specificity of the SCMVP. Therefore, we believe that a massive improvement in the ability of computer software to distinguish critical leaks from these complicating factors with an adequate alarm bench test is the next challenge for demonstrating the reliability of the SCMVP hardware and software. This prototype might still be too bulky, unsophisticated, or underperforming (e.g. slow response speed of the CO\textsubscript{2} sensor) for clinical use mainly because of the reduced cost of the equipment. The next generation of the SCMVP awaits further refinement.

The troubleshooting time did not differ significantly between the SCMVP and the conventional system in scenarios 1, 3, and 4. A possible reason for the significant reduction in the time required to solve scenario 2 for the SCMVP is that the monitor display pinpointed the site of the leak in this scenario. The SCMVP monitor did not always clearly pinpoint the site of the leak due to the limited number of sensors in the prototype. Increasing the number of sensors can provide more detailed information, which will allow the healthcare provider to identify the site of the leak more easily. However, the more sensors that are installed, the more expensive the SCMVP becomes; thus, the optimal balance between cost and benefit needs to be explored. In scenario 4 involving unplanned tracheal extubation, identification of oesophageal intubation seemed to be difficult even though the display pattern activated by this scenario substantially narrowed the suspected circuit components to check. A probable reason for this finding may be that diagnosis of unplanned extubation requires diagnostic procedures such as auscultation of the chest. An additional reason for the lack of difference in troubleshooting times between the two systems might be that the participants did not have enough time to become accustomed to the SCMVP. We anticipate that performance in identifying the sites of leaks will improve with increased use of the SCMVP.

In addition to the development of novel alarm systems, educational sessions on how to handle a gas leak may also shorten the troubleshooting time. Therefore, approaches to promote patient safety during mechanical ventilation should include both the improvement of alarm systems and the training on management of incidents related to respirators. There are several reports that a cognitive aid is helpful for managing medical crises when it is actively used.\textsuperscript{12–15} However, these reports also noted that the cognitive aids were not always used appropriately or that some study populations were unaware of their availability. Therefore, the next step in the evaluation of the SCMVP will be to compare the usefulness of this system for troubleshooting of air leaks with that of medical education with and without cognitive aids. It will be also interesting to study the usefulness of the SCMVP itself as an intelligent cognitive aid for medical education and clinical practice.

In conclusion, we found that the SCMVP decreased the troubleshooting time and improved the success rate of troubleshooting of simulated leaks in a respiratory circuit through an increase in prompt identification of leaks. More studies must be conducted using a refined SCMVP and a broader range of scenarios before generalized conclusions can be made. Human studies will also be needed to test the applicability of the refined SCMVP in clinical settings.
Authors’ contributions
K.M.: study design, data analysis, and manuscript preparation; S.M., Y.F., H.T., T.M., and T.T.: data collection and data analysis; T.H.: development of the SCMVP; K.E. and Y.U.: study design; T.A.: study design, conduct of the study, data analysis, and manuscript preparation.

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Declaration of interest
Sango Co., Ltd. is developing the SCMVP for the purpose of commercialization. T.H. receives a salary from SANGO Co., Ltd.

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Appendix: Components of the SCMVP

Figures A1–A3.

Fig A1 Component 1. Close-up view of the multi-sensor package for the respiratory circuit.

Fig A2 Component 2. (A) Photograph of the installed respiratory circuit disconnection detecting system. (B) Photograph of the sensor unit of the respiratory circuit disconnection detecting system. LED, light-emitting diode.

Fig A3 Component 5. Photograph showing warming holder for the heat-moisture exchanger.