International Journal of Innovative Computing, Information and Control
Volume **21**, Number **3**, June **2025**
ICIC International ©2025 ISSN 1349-4198
pp. **759–767**

THE EFFECT OF LEAKAGE ON INHALED OXYGEN CONCENTRATION IN COMBINED VENTILATOR AND OXYGEN THERAPY DURING EXACERBATIONS OF CHRONIC OBSTRUCTIVE PULMONARY DISEASE: A COMPARATIVE STUDY USING THE STATE-OF-THE-ART VOCSN, HAMILTON-C1, AND VELA

Takeshi Ifuku[1], Kazuto Doi[2,*], Yoshifumi Kawakubo[3], Takashi Hitosugi[1]
Mitsuhiro Nishitani[4] and Takeshi Yokoyama[1]

[1]Department of Dental Anesthesiology
Faculty of Dental Science
Kyushu University
3-1-1 Maidashi, Higashi-ku, Fukuoka 812-8582, Japan
if1290523@ybb.ne.jp; hitosugi.takashi.724@m.kyushu-u.ac.jp; yokoyama@dent.kyushu-u.ac.jp

[2]Department of Engineering, Medical Engineering Course
Faculty of Engineering
Nagasaki Institute of Applied Science
536 Aba-Machi, Nagasaki 851-0193, Japan
*Corresponding author: DOI_Kazuto@NiAS.ac.jp

[3]Osaka Jikei College Office for Establishment of University
1-2-8 Miyahara, Yodogawa-ku, Osaka 532-0003, Japan
y-kawakubo@juhs.ac.jp

[4]Department of Nephrology
Daimon Clinic for Internal Medicine, Nephrology and Dialysis
400-1 Oshino, Nonoichi-shi, Ishikawa 921-8802, Japan
sdbjr617@gmail.com

Received August 2024; revised November 2024

Abstract. *The combination of home oxygen therapy (HOT) and home mechanical ventilation (HMV) faces issues like decreased fraction of inspired oxygen (FiO_2) due to leaks. Traditional HMV devices have insufficient leak compensation functions. However, the state-of-the-art VOCSN, with an oxygen concentrator, is believed to mitigate leaks and maintain FiO_2. This study compared the impact of leaks on FiO_2 using VOCSN, Hamilton-C1, and VELA. A model lung simulated COPD patients, and FiO_2 and leak levels were measured. Results showed that VELA and Hamilton-C1 had higher FiO_2 compared to VOCSN, with no difference between VELA and Hamilton-C1. This suggests VOCSN prioritizes ventilation volume over FiO_2 with leaks. Hamilton-C1 maintained high FiO_2 when HOT and HMV were used together in home healthcare.*
Keywords: Home oxygen therapy (HOT), Home mechanical ventilation (HMV), Chronic obstructive pulmonary disease (COPD)

1. **Introduction.** In Japan, there are approximately 3 million patients with chronic obstructive pulmonary disease (COPD) [1]. Globally, it has been reported that over 250 million people are affected by COPD [2]. COPD has a profound impact on both individual health and the healthcare economy [3]. In Japan, there has been a shift from medical

DOI: 10.24507/ijicic.21.03.759

institutions to home care, with COPD accounting for approximately 45% of patients using home oxygen therapy (HOT) [4]. Furthermore, in severe cases, there is a combination therapy of HOT and home mechanical ventilation (HMV) for type II respiratory failure patients, but there are still many challenges to be addressed. Noninvasive positive pressure ventilation (NPPV) in HMV has demonstrated its usefulness in COPD patients, but when leaks occur from the mask, the fraction of inspired oxygen (FiO_2) supplied to the alveoli decreases [5]. We have conducted simulated experiments assuming home-based COPD patients to verify the extent of the decrease in FiO_2 supplied to the alveoli due to leaks from the mask [5,6]. Previously, for patients with insufficient oxygen in their blood, home oxygen therapy (HOT) has been used as a treatment method to inhale the insufficient oxygen outside the hospital, such as at home. However, as the symptoms of COPD progress, respiratory strength weakens, leading to oxygen deficiency and retention of carbon dioxide in the body [7,8]. There is a method of connecting a ventilator and an oxygen concentrator with a tube to operate them simultaneously, aiming to improve this condition. However, it has been reported that this method is not suitable for treatments that require high FiO_2 levels [6,9]. It has been reported that, unlike in the acute phase, it is difficult to maintain the target FiO_2 value in the chronic phase due to leaks or the combined use with a ventilator, even with oxygen supplementation [10]. Therefore, in this study, we verified whether the measurement of FiO_2 is affected by leaks or the combined use with a ventilator using the world's first ventilator equipped with an oxygen concentrator.

In this study, we aim to collect actual measurement data to investigate the impact of leaks in the combination of HMV and HOT on FiO_2, with the goal of providing reference data to achieve hospital-level oxygen therapy in home care. This study aims to serve as foundational research covering artificial ventilators used in home care, ranging from conventional models to state-of-the-art devices. In home care, there is no oxygen piping available, while hospitals have oxygen piping that allows for stable oxygen therapy unaffected by leaks [10]. The ultimate goal of this study is to verify whether the state-of-the-art ventilator, VOCSN, can maintain FiO_2 levels comparable to those achieved in hospital-based oxygen therapy, in conjunction with comparisons to prior research.

2. Methods.

We used the TTL model lung (manufactured by Michigan Instruments), which is also employed in prior studies, as a simulated lung model for COPD patients. In this study, we followed the established practice of using the TTL model lung for research on simulated COPD lungs. Additionally, since this study involves a ventilator equipped with an oxygen concentrator that differs from previous research, it is essential to accurately measure the changes in FiO_2 levels due to leaks and the FiO_2 levels within the lung without leaks. The TTL model lung was chosen because it is a reliable measurement lung. The left lung of the TTL model lung was forced to ventilate and the right lung was made to sense inspiratory effort. Spontaneous respiration was also produced by attaching a lift bar between the left and right lungs. To simulate NPPV, we created an adapter with oxygen supply and leak ports, which was installed between the inspiratory circuit of the ventilator and the Y-piece. Through this adapter, oxygen was added to the TTL model lung and leaks were generated (Figure 1). The leak rates were set to 0, 5, and 10 L/min. We aimed to compare leak rates with prior studies, as it has been reported in actual clinical settings that NPPV can experience air leaks ranging from 5 L/min to 10 L/min, as noted in [9-11], and this study was conducted accordingly. The leak amount was constantly measured using the flow analyzer PF-300 during the experiment. We tested three different models of ventilators: VOCSN (Ventec Life Systems Inc. USA), VELA (Vyaire Medical USA), and Hamilton-C1 (HAMILTON MEDICAL AG SWISS). The

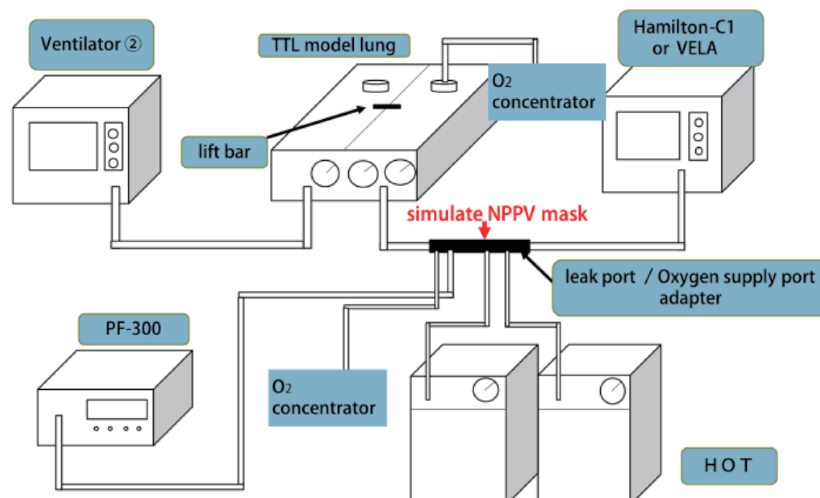

FIGURE 1. Schematic diagram of the circuit without an integrated oxygen concentrator (Hamilton-C1, VELA). Ventilator② is a ventilator designed to artificially generate spontaneous respiration, similar to prior research [5,6,10,11].

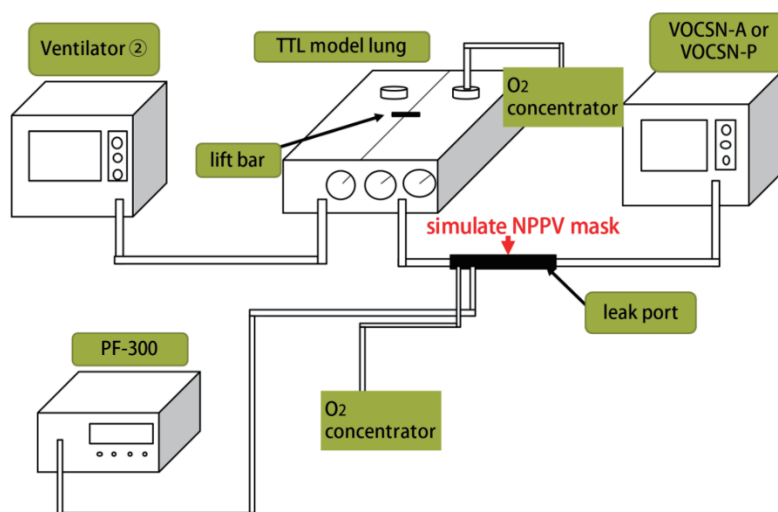

FIGURE 2. Schematic diagram of the state-of-the-art ventilator with an integrated oxygen concentrator (VOCSN-A and VOCSN-P). Ventilator② is a ventilator designed to artificially generate spontaneous respiration, similar to prior research [5,6,10,11].

VOCSN is a respiratory care system that integrates the functions of a ventilator, oxygen concentrator, secretion management device, suction device, and nebulizer. For the latest model, VOCSN, which has an integrated oxygen concentrator in the ventilator, we only used the leak port (Figure 2). The VOCSN had two dedicated circuits (VOCSN-A and VOCSN-P), and measurements were taken under the same conditions for both circuits. The settings of each HMV device were based on the prior research [5,6,9,10] (Table 1). To minimize statistical errors, we performed 10 rounds of 5-minute measurements.

Statistical Analysis. To assess the normality of the data, the Shapiro-Wilk test was performed. Additionally, comparisons between two groups were conducted using the Student's t-test. For comparisons among multiple groups and variables, the Holm method was employed as a multiple comparison correction to control for Type I errors. Statistical

Table 1. Setting conditions

	Hamilton-C1	VELA	VOCSN-A	VOCSN-P
Mode	NIV	A/C	AC-Volume	AC-Volume
Respiratory Rate	12 breaths/min	12 breaths/min	12 breaths/min	12 breaths/min
Inspiratory Time	1.2 sec	1.2 sec	1.2 sec	1.2 sec
Tidal Volume	500 mL	500 mL	500 mL	500 mL
PEEP*	5 cmH_2O	5 cmH_2O	5 cmH_2O	5 cmH_2O
Leak Compensation	ON	ON	ON	ON

*PEEP: Positive end expiratory pressure

analyses were conducted using R statistical software (version 3.5.0, The R Foundation for Statistical Computing, Vienna, Austria). A P-value of less than 0.05 was considered to indicate statistical significance between groups. For the R code, see the Appendix.

3. **Results.** Upon analyzing the ventilators based on different leak levels, the Hamilton-C1 showed higher FiO_2 values, but there was no statistically significant difference observed (Figure 3).

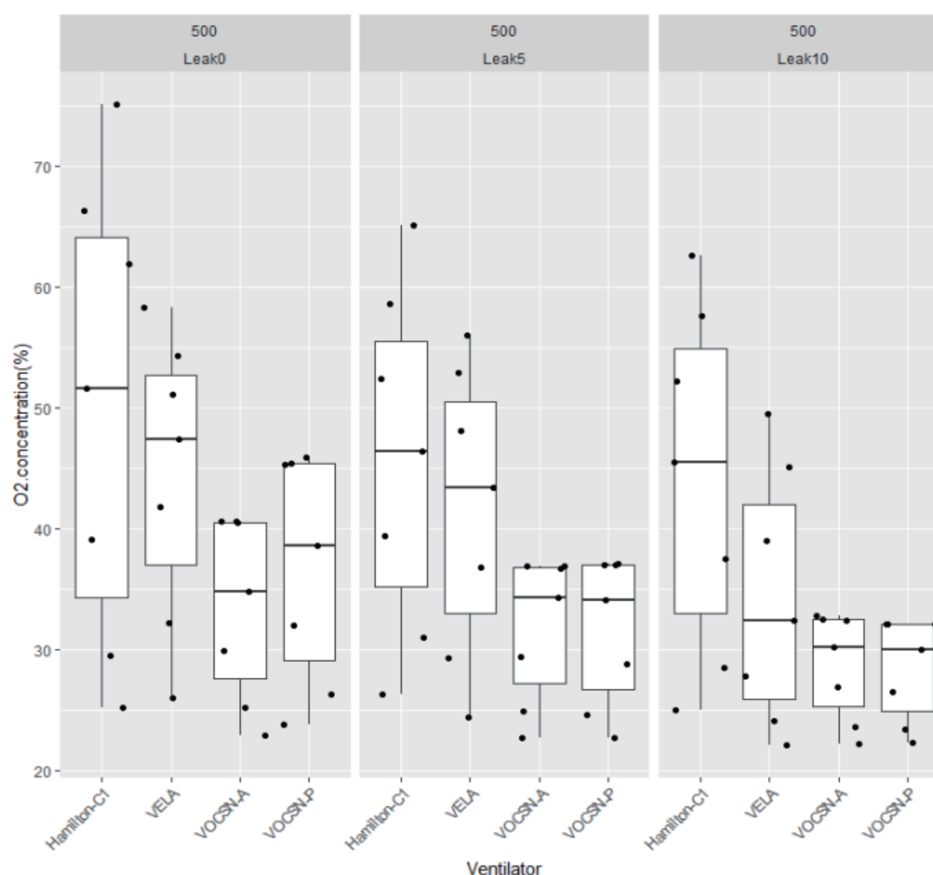

Figure 3. Analysis of ventilators based on different leak levels

Regarding individual ventilators, Hamilton-C1 exhibited significantly higher FiO_2 values compared to VOCSN-A and VOCSN-P, with $P < 0.05$. Similarly, VELA also showed significantly higher FiO_2 values compared to VOCSN-A and VOCSN-P. However, there were no significant differences observed between Hamilton-C1 and VELA, or between VOCSN-A and VOCSN-P (Figure 4).

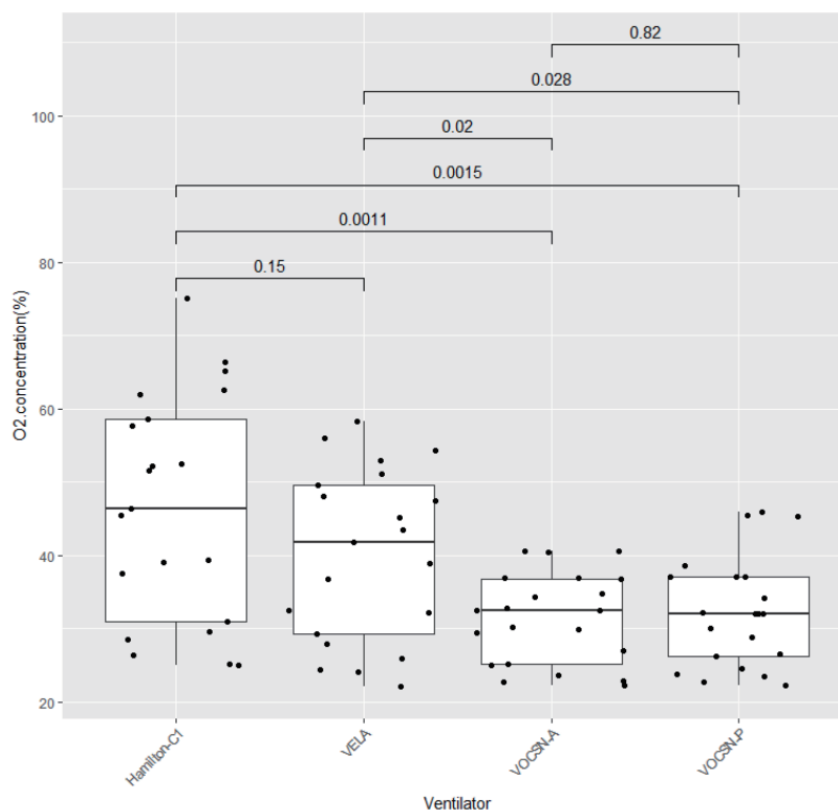

FIGURE 4. Comparison of FiO_2 values among different mechanical ventilators

4. **Discussion.** In this study, we evaluated the FiO_2 values during the combined use of NPPV and home oxygen therapy (HOT), building upon previous study [10]. In home care settings, the use of oxygen concentrators, oxygen cylinders, or liquid oxygen systems is commonly employed for HOT. Oxygen therapy combining HMV and HOT is utilized for acute exacerbations of COPD and severe cases of respiratory failure. However, studies have shown that O_2 supplied by HOT is diluted by HMV leakage compensation due to leakage from the NPPV, resulting in low O_2 concentrations [11]. From this study, it is clear that Hamilton-C1 can maintain high FiO_2 values for oxygen therapy in combination with ventilators in home care. The reason Hamilton-C1 was able to maintain higher FiO_2 values than any of the HMVs may be that it was initially set to compensate for a ventilation leak rate of 2 L/min, so it responded to artificial leaks of 5 L/min and 10 L/min by increasing compensatory ventilation but not beyond 2 L/min. This suggests that excessive mixing of supplied oxygen from HOT with air was avoided, contributing to the higher FiO_2 values. This finding supports the notion that the Hamilton-C1 has stricter ventilation management concerning leak control compared to other HMV devices, as also reported by Doi et al. [5].

Conversely, the VELA showed lower FiO_2 values compared to the Hamilton-C1, indicating the presence of leak compensation exceeding 2 L/min. It is likely that the decrease in FiO_2 values resulted from the mixing effect due to compensatory ventilation exceeding 2 L/min. Supporting this, the VELA increased ventilation without alarm even when the HOT oxygen supply exceeded 10 L/min [5]. In contrast, the Hamilton-C1 experienced ventilation cessation when the HOT oxygen supply exceeded 7 L/min. This is a significant and noteworthy finding. It has been demonstrated that the amount of compensatory ventilation varies among HMV models, resulting in different FiO_2 values with the amount of leakage even with the same oxygen supply.

Furthermore, no significant differences were observed in the VOCSN-A and VOCSN-P models, which are the state-of-the-art HMV devices equipped with integrated oxygen concentrators. Although the VOCSN models can deliver 6 L/min of oxygen while managing artificial respiration, they exhibited lower FiO_2 values compared to other HMV devices [12]. The VOCSN is HMV that can be introduced for treatment of low FiO_2 values at present. Although HMVs with HOT functions are compact, space-saving, and easy to use, it is currently difficult to achieve FiO_2 values exceeding 40%. Further improvements are expected to make it applicable to patients with severe COPD [9].

5. **Conclusions.** This study demonstrates that the Hamilton-C1 maintains significantly higher FiO_2 values compared to other HMV devices when used in conjunction with HOT. This improved performance is attributed to its effective management of ventilation leaks. In contrast, the VELA showed reduced FiO_2 values due to excessive leak compensation. Although VOCSN models incorporate advanced technology, they did not achieve higher FiO_2 values.

There are limitations to this study. The experiments were conducted using a simulated lung model, and various types of HOT devices, such as oxygen cylinders and liquid oxygen systems, were not included. It is necessary to expedite further data collection to compare the impact on FiO_2 values when using these different types of HOT devices. In the future, we plan to conduct studies using animals and human subjects, considering various diseases and environmental conditions, to further advance and implement artificial respiration devices in home oxygen therapy.

Acknowledgment. This study was supported by a grant from JSPS KAKENHI (Grant No. JP22K18245).

REFERENCES

[1] Y. Fukuchi, M. Nishimura, M. Ichinose, M. Adachi, A. Nagai, T. Kuriyama, K. Takahashi, K. Nishimura, S. Ishioka, H. Aizawa and C. Z. Affiliations, COPD in Japan: the Nippon COPD Epidemiology study, *Respirology*, vol.9, no.4, pp.458-465, 2004.
[2] R. Tal-Singer and J. D. Crapo, COPD at the time of COVID-19: A COPD Foundation perspective, *Chronic Obstructive Pulmonary Diseases (Miami, Fla.)*, vol.7, no.2, pp.73-75, 2020.
[3] F. Kirsch, A. Schramm, L. Schwarzkopf, J. I. Lutter, B. Szentes, M. Huber et al., Direct and indirect costs of COPD progression and its comorbidities in a structured disease management program: Results from the LQ-DMP study, *Respir. Res.*, vol.20, no.1, 215, 2019.
[4] The Japanese Respiratory Society, *White Paper on Home Respiratory Care*, p.27, 2013.
[5] K. Doi, M. Nishitani, M. Doi, Y. Yaegash, M. Ando and J. Kadota, Influence of leakage from non-invasive positive pressure ventilation mask on FiO_2 value delivered by home oxygen therapy concentrator: A bench study on simulating patients with chronic obstructive pulmonary disease, *Health*, vol.10, no.7, pp.919-927, 2018.
[6] T. Hishinuma, M. Nishitani, N. Kumano, M. Ymasaki, S. Turukubo, T. Kimura and K. Doi, Evaluation study of inhaled oxygen concentration with combined use of ventilator and liquid oxygen in home oxygen therapy, *Journal of Advanced Science*, vol.35, 2023.
[7] A. Anzueto and M. Miravitlles, Pathophysiology of dyspnea in COPD, *Postgrad. Med.*, vol.129, no.3, pp.366-374, 2017.
[8] B. Csoma, M. R. Vulpi, S. Dragonieri, A. Bentley, T. Felton, Z. Lázár and A. Bikov, Hypercapnia in COPD: Causes, consequences, and therapy, *J. Clin. Med.*, vol.11, no.11, 3180, 2022.
[9] K. Doi, T. Hishinuma, T. Ifuku and M. Nishitani, Report on the effect of leakage on inhaled oxygen concentration in combined ventilator and oxygen therapy at home, *International Journal of Biomedical Soft Computing and Human Sciences*, vol.28, no.1, pp.9-14, 2023.
[10] K. Doi, M. Nishitani, M. Doi, T. Ifuku and K. Murotani, Leakage from non-invasive positive pressure ventilation therapy masks affects fraction of inspired oxygen: Comparison of home- and institution-delivered oxygen therapy on simulated patients with chronic obstructive pulmonary disease, *International Journal of Innovative Computing, Information and Control*, vol.20, no.2, pp.497-508, 2024.

[11] P. Goutorbe, E. Daranda, Y. Asencio, P. Esnault, B. Prunet, J. Bordes et al., Leaks can dramatically decrease FiO_2 on home ventilators: A bench study, *BMC Research Notes*, vol.6, 282, 2013.
[12] T. Blakeman, J. M. Fowler, A. Salvator and D. Rodriquez, Maximizing oxygen delivery in portable ventilators, *Mil. Med.*, DOI: 10.1093/milmed/usab561, 2022.

Appendix.

```
library(tidyverse)
library(ggpubr)

x<-read.table("clipboard",header=t)
x2<-c(rep(1:84))

ggplot(data=x,aes(x=Ventilator,y=O2.concentration,
group=Ventilator))+
geom_boxplot()+
geom_jitter()+
facet_wrap(~Vt+reorder(Leak,x2))+
labs(x="Ventilator",y="O2.concentration(%)")+
theme(axis.text.x=element_text(angle=45,hjust=1))

Figure 3.



p1<-ggplot(data=x,aes(x=Ventilator,y=O2.concentration,group=
Ventilator))+
geom_boxplot()+
geom_jitter()+
labs(x="Ventilator",y="O2.concentration(%)")+
theme(axis.text.x=element_text(angle=45,hjust=1))

p1+
stat_compare_means(comparison=list(c("Hamilton-C1","VELA"),
c("Hamilton-C1","VOCSN-A"),c("Hamilton-C1","VOCSN-P"),
c("VELA","VOCSN-A"),c("VELA","VOCSN-P"),
c("VOCSN-A","VOCSN-P")),
map_signif_level=c("*"=0.05),test="t.test",
p.adjust.method="holm")

Figure 4.
```

Author Biography

Takeshi Ifuku received his Ph.D. degree from the Graduate School of Dentistry at Kyushu University, Japan, in 2025. He has obtained qualifications as a clinical laboratory technician and clinical engineering technologist. His present research interests include clinical engineering, especially interested in hemodialysis and stem cell.

Kazuto Doi received a Doctor of Medicine degree from Oita University, 2021. He is presently a Lecturer of the Department of Engineering, Medical Engineering Course, Nagasaki Institute of Applied Science, Japan. His current research theme is clinical engineering, especially interested in home oxygen therapy.

Yoshifumi Kawakubo received his Ph.D. from the Graduate School of Dentistry at Kyushu University, Japan, in 2015. He obtained his clinical engineer license in 1992. From 1992 to 2011, he worked as a clinical engineer at Tokushima Prefectural Miyoshi Hospital, and from 2011 to 2017, at Tokushima Prefectural Central Hospital.

He is currently an Associate Professor in the Department of Clinical Engineering, Faculty of Health Care Sciences, at Jikei University of Health Care Sciences, Japan. His research interests focus on biomedical engineering. He has published over 20 papers in academic journals and conducts research funded by government grants and corporate sponsors.

Takashi Hitosugi graduated from Nihon University (DMD), Japan, 2001, Ph.D. (Dentistry) from Nihon University, Japan, 2007, Licensed to dentistry in the Federal Republic of Germany, 2014. He was affiliated with St. Luke's international hospital, Nihon University Graduate School, University of Freiburg. Currently, he is a Lecturer at Department of Dental Anesthesiology, Faculty of Dental Science, Kyushu University. His specialty includes dental anesthesiology, oral and maxillofacial surgery.

Mitsuhiro Nishitani obtained a qualification as a Clinical Engineering. In 2007, he graduated from Graduate School of Medicine, Kanazawa University and obtained a Master of Medical Science degree. He has been working as a clinical engineering for Dialysis Technician. His current research theme is clinical engineering, especially interested in assessing fluid volume in hemodialysis patients.

Takeshi Yokoyama graduated from School of Dentistry, Osaka University in 1990 and obtained the degree of DDS. In 1994, he completed his postgraduate studies at the Graduate School of Medicine, University of Tokyo and was awarded the degree of Ph.D. He worked as an Associate Professor at the Department of Anesthesiology, Kochi University of Medical Science from 2004 to 2009.

He is currently a Chair Professor at the Department of Dental Anesthesiology, Faculty of Dental Science, Kyushu University. His research interests include anesthesia and perioperative management. He has given more than 100 presentations at international conferences and published more than 100 research papers and 140 case reports in peer-reviewed journals.