Prevention of droplet dispersal with "e-mask": A new daily use endoscopic mask during bronchoscopy

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SUMMARY AT A GLANCE

A new type of endoscopic mask (e-mask) reduced the number and volume of dispersed airborne particles during bronchoscopy. No significant differences in adverse events or complications during bronchoscopy were observed between the use of the e- mask and a patient wearing no mask, supporting its enhanced protection and safety during bronchoscopy.

ABSTRACT

Background and objective: Bronchoscopy is an airborne particle-generating procedure. However, few methods for safe bronchoscopy have been developed. To reduce airborne particles during bronchoscopy, we created an "e-mask," which is a simple, disposable mask for patients. Our objective was to evaluate the e-mask's protective ability against airborne particles and to assess respiratory adverse events and complications.

Methods: Patients with stage 2-4 chronic obstructive pulmonary disease were excluded. We performed visualization and quantifying experiments on airborne particles with and without the e-mask. We prospectively evaluated whether wearing the e-mask during bronchoscopy was associated with the incidence of patients requiring >5 L/min oxygen to maintain >90% oxygen saturation, and patients with >45 mmHg end-tidal carbon dioxide ($EtCO_2$) elevation, in addition to complications, compared to historical controls.

Results: In the visualization experiment, more than ten thousand times of airborne particles were generated without the e-mask than with the e-mask. The volume of airborne particles was significantly reduced with the e-mask, compared to that without the e-mask ($P = 0.011$). Multivariate logistic regression analysis revealed that wearing the e-mask had no significant effect on the incidence of patients requiring >5 L/min oxygen to maintain >90% oxygen saturation, ($P = 0.959$); however, wearing the e-mask was a significant factor in >45 mmHg $EtCO_2$ elevation ($P = 0.026$). No significant differences in complications were observed between the e-mask and control groups (5.8% vs. 2.5%, $P = 0.395$).

Conclusion: Wearing the e-mask during bronchoscopy significantly reduced the generation of airborne particles during bronchoscopy without increasing complications.

Short title:

Utility of e-mask during bronchoscopy

Keywords:

bronchoscopy, COVID-19, coronavirus disease, airborne particle, prevention, respiratory protective devices, e-mask

INTRODUCTION

Severe acute respiratory syndrome coronavirus 2, which is the causative agent for the ongoing coronavirus disease 2019 (COVID-19) pandemic, has spread worldwide and resulted in high mortality rates globally. It is transmitted through close contact with infected respiratory droplets, contact surfaces, and aerosols including small airborne particles (ABPs).[1,2] Bronchoscopy increases the risk of respiratory virus transmission via respiratory droplets and aerosols.[3] Previous reports on the social guidelines for bronchoscopy during COVID-19 pandemic have recommended that healthcare workers use N-95 respirators or powered air purifiers in negative pressure rooms, along with gowns, gloves, caps, and personal protective equipment (PPE) such as wrap-around eye protectors.[4-6]

Several studies have reported on the use of protective barriers to prevent the spread of ABPs from patients undergoing ABPs-generating procedures.[7-9] However, there is a lack of evidence regarding the effectiveness of these barriers, and some studies suggest that they may interfere with and pose additional risk to airway management.[10-12]

To minimize ABP dispersal during bronchoscopy, we developed a simple and disposable mask with help from the Japanese mask industry.[13] This "e-mask" has a 10-mm slit in the center for insertion of a bronchoscope and a 6-mm slit on both sides for insertion of a suction catheter.

Herein, we used visualization experiments to evaluate the ability of the e-mask to prevent diffusion of ABPs and assessed the respiratory adverse events and complications in patients wearing the e-mask during bronchoscopy.

METHODS

Visualization experiments

Mask design

As previously reported, the e-mask was designed as a non-woven surgical mask that is 175-mm wide and 95-mm long, with a 160-mm elastic.[13] The mask has a 10-mm cross-shaped slit (endoscope hole) in the center and X-shaped slits (catheter holes) on either side (Figure 1a). Further details are provided in Appendix S1 in the Supporting Information.

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Acrylic box for visualization of ABPs during spraying

For the spray experiment, we prepared an acrylic box (Acrylic Water Tank 155L PW90 1-2982-03, AS ONE, Osaka, Japan) with dimensions 90×45×45 cm (Figure 2a). Details are provided in Appendix S1 in the Supporting Information.

Visualization of the scattered ABPs using the acrylic box

Red water-based paint dissolved in water was sprayed five times using a mist sprayer (Elephant mist sprayer, FURUPLA, Tokyo, Japan) through the hole at the bottom of the box.

Quantification of the scattered ABPs using the acrylic box

Fluorescent-green spray paint (Asahi-pen, Osaka, Japan) was used to quantitatively evaluate the effectiveness of the e-mask in preventing aerosol scattering by measuring the fluorescence. A 10-cm square black paper was attached on the right, left, and top sides of the box, and at a height of 10 cm above the bottom hole. The fluorescent paint was sprayed through the bottom hole for 10 s, and the fluorescence on the black paper was measured using the IVIS Spectrum CT *in vivo* imaging system (PerkinElmer, Waltham, MA, USA) at 465-nm excitation light and 540-nm fluorescence. The background-subtracted fluorescence intensity was compared quantitatively with and without the e-mask.

Visualization of the ABPs using ultra-high-sensitive camera

Details are provided in Appendix S1 in the Supporting Information.

Quantification of the ABPs using ultra-high-sensitive camera

Details are provided in Appendix S1 in the Supporting Information.

Direct counting of the ABPs using a particle counter

A droplet counting system "Type-S" (SHIN-NIHON-Kucho), which has a 445-nm laser to reflect the particles, was used for the direct count. The experiments were performed at least thrice.

Visualization of the airborne mist using ultra-high-sensitive camera

Details are provided in Appendix S1 in the Supporting Information.

Simulation of the aerosol spread via air-fluid flow analysis

Details are provided in Appendix S1 in the Supporting Information.

Feasibility manikin study on the use of e-mask during bronchoscopy

Details are provided in Appendix S1 in the Supporting Information.

. The sample size was set to at least 30 cases, referred to another crossover manikin study.[14]

Patient application of e-mask use during bronchoscopy

We prospectively enrolled patients who underwent flexible bronchoscopy using the e-mask (e-mask group) between November 1, 2020 and February 28, 2021. We compared the e-mask group with consecutive patients who underwent bronchoscopy without the e-mask (control group) between April 1, 2011 and September 30, 2011 since the record of EtCO2 during bronchoscopy was only during this period of time in 2011. Further details are provided in Appendix S1 and Figure S1 in the Supporting Information.[15-20]

Statistical analysis

Visualization experiments

Data are expressed as mean ± SEM of a minimum of three experiments. Statistical analyses were performed using the Prism software (GraphPad, San Diego, CA, USA). For two-group comparisons, Student's t-test was used. Statistical significance was set at $P < 0.05$.

Patient application of e-mask use during bronchoscopy

We estimated that at least 88 patients (44 in e-mask group and 44 in control group) were required to be enrolled in order the study would have 80% power to detect a significant between-group difference in the change in clinical outcomes, with a medium effect size of 0.6 standard deviation. We set the required number of patients in e-mask group to 50 to account for dropouts. We calculated our data as described in Appendix S1 in the Supporting Information..[21,22] The analyses were performed using IBM SPSS Statistics (version 28; IBM, Armonk, NY).

RESULTS

Visualization experiments

Scheme of the e-mask, and visibility during bronchoscopy with or without the e-mask

To determine the appropriate mask structure, we inserted bronchoscopes through masks with 6-, 10-, and 15-mm endoscope slits, and observed the operability and tested the gaps. Considering that the bronchoscope size is about 3–7 mm, and the upper gastrointestinal endoscope is about 5–9 mm, we finally decided on an endoscope hole of 10 mm. E-mask is similar to a surgical mask with a slit which is hand-made by the operator. However, handmade creation is unsanitary and cumbersome, and the size of the slit differs each time, making it difficult to determine the precise protective effect. Therefore, we decided to mass-produce this mask, which has a 10-mm slit in the centre for insertion of the fiberscope and a 6-mm slit on both sides for the suction tube (Figure 1a); this mask was named the "e-mask" which stands for "endoscopic" mask, "easy to use", and "economical" mask. The pleats of this mask are more ingenious than those of common surgical masks, and the slit is placed at the center of the mask (Figure 1b). Since the electrically-charged filter is attached to the surface woven fabric, the slit remains closed unless it is used for bronchoscope insertion (Figure 1c). Visibility during bronchoscopy with or without the e-mask is shown in Figure 1d.

Demonstration of the effectiveness of the e-mask in preventing ABPs

To visualize the preventative effect of the e-mask on ABPs, water mixed with water-based red paint was sprayed five times through the hole in the bottom of the acrylic box (Figure 2a). Without the e-mask, a large amount of paint was observed on the top and bottom and left and right walls of the box. In contrast, when the e-mask was used, little paint was observed inside the acrylic box, with more paint observed on the inside of the e-mask (Figure 2b and Supplementary Video 1). Next, to quantify the ABPs in the acrylic box, fluorescent-green dye was sprayed for 10 s. The fluorescent intensity on the black paper attached inside the acrylic box was measured using a fluorescence imaging system (Figure 2c). The fluorescence on the black paper was barely visible with the use of the e-mask (Figure 2c). A significant decrease

in fluorescence intensity was observed at all positions with the e-mask, compared to that without the e-mask (n = 3; above, $P = 0.020$; left, $P < 0.001$; right, $P = 0.012$; head, $P = 0.002$) (Figure 2d).

Next, to visualize the ABPs from the mouth and nose, highly sensitive visualization was performed using an ultra-high-sensitive camera (ViEST system). The ABP visualization experiment using the ViEST system is shown in Figure 2e. The light source was a 400–410-nm wavelength. An ultra-high-sensitive camera was aligned with the target (ABPs), aimed above the nose and mouth. Coughing images taken with the ViEST system demonstrated that almost no ABPs were dispersed when the e-mask was used; however, without the e-mask, a large amount of ABPs were observed during coughing, which lingered in the air until 5 s later (Figure 2f and Supplementary Video 2). Analysis and quantification of the ABPs from the video showed a significant decrease in the ABPs from the mouth and nose with use of the e-mask, compared to without the e-mask (n = 3, $P = 0.011$). Without the e-mask, the increase in the ABPs, which were counted as pixels during the experiment, was observed to peak at ~1 s after coughing, gradually decreased at 7 s, and was still floating at 6 s after coughing. With the e-mask, no increase in ABPs was observed (Figure 2h). Direct counting of the ABPs was performed using a type-S particle counting system (Figure 2i). The particle counts were significantly decreased with the e-mask (n = 12, $P < 0.001$) (Figure 2j). To visualize the aerosol flow from the mouth, we performed mist visualization using the ViEST system (Figure 2k). The ViEST system images of the mist demonstrated that leakage from the e-mask was only through the gap between the nose and the e-mask, whereas the mist went straight forward from the mouth without the e-mask (Figure 2l and Supplementary Video 3). Collectively, we experimentally proved that the e-mask can effectively reduce particulate matter.

Simulation of the spread of small ABPs (aerosols) with or without the e-mask

Next, we simulated the spread and flow of the ABPs using an air-flow simulation software (Cradle CFD/scFLOW software). The simulation set is indicated in Figure 3a. The simulations revealed that without the e-mask, the aerosol from the mouth after coughing diffused straight down, while with the e-mask, only a small amount of aerosol leaked through the gap between the nose and the mask (Figure 3b and Supplementary Video 4). Based on these results, it was predicted that the e-mask can prevent airflow, which mimics aerosols, due to coughing to a large extent. These data indicated that the e-mask can significantly reduce exposure to the environment during bronchoscopy.

Feasibility manikin study on the use of the e-mask during bronchoscopy

Details are provided in Appendix S2 and Figure S2 in the Supporting Information.

Clinical study on patients who wore the e-mask during bronchoscopy

Study Patients

We included 52 patients in the e-mask group and 105 patients in the control group. A total of 92 propensity score-matched patients were finally included: 52 patients in the e-mask group and 40 patients in the control group. After propensity score matching, the baseline clinical characteristics between the two groups were comparable, although the ratio of patients who never smoked and the vital capacity (predicted percentage) in the control group were significantly higher than those in the e-mask group before propensity score matching (Table 1).

Changes in SpO_2, $EtCO_2$, systolic blood pressure (SBP), heart rate (HR), and respiratory rate (RR) in the e-mask group during bronchoscopy

For the changes in SpO_2, $EtCO_2$, SBP, HR, and RR in the e-mask group during bronchoscopy, details are provided in Figure S3 in the Supporting Information.

Primary and secondary endpoint

The incidence of patients who required >5 L/min oxygen (O2) to maintain >90% saturation of percutaneous oxygen (SpO_2) was not significantly different between the e-mask and control groups (19.2% vs. 35.0%, $P = 0.088$). Moreover, the incidence of patients with >45 mmHg end-tidal carbon dioxide ($EtCO_2$) elevation was not significantly different between the e-mask and control groups (32.7% vs. 15.0%, $P = 0.052$). No significant complications were detected between the e-mask and control groups (5.8% vs. 2.5%, $P = 0.395$).

Factors affecting respiratory adverse events during bronchoscopy

Multivariate logistic regression analysis revealed that baseline SpO_2 was the only factor affecting the incidence of patients requiring >5 L/min O_2 to maintain >90% SpO_2 ($P = 0.028$) (Table 2). In contrast, the factors affecting the incidence of patients with >45 mmHg $EtCO_2$ elevation were the use of the e-mask and smoking status ($P = 0.026$, $P = 0.019$, respectively) (Table 3).

DISCUSSION

Bronchoscopy is associated with the risk of infections transmitted through respiratory droplets and aerosols, commonly known as aerosol-generating procedures.[3] Thompson et al. measured the amount of influenza A H1N1 (2009) RNA in the aerosols in the vicinity of H1N1-positive patients undergoing aerosol-generating procedures; bronchoscopy was observed to pose a greater risk to ABPs than that encountered in the baseline samples.[23] Furthermore, pulmonary tuberculosis was unexpectedly diagnosed in 3.2%–4.6% of patients when diagnostic bronchoscopy with or without radial endobronchial ultrasound was performed.[24,25] Although topical use of lidocaine or sedatives during bronchoscopy should be offered to patients who undergo bronchoscopy to prevent excessive coughing and provide patient comfort, they do not completely reduce the cough reflex.[19] Therefore, protection during endoscopic procedures should be considered not just for healthcare workers (with PPE such as N95 masks, face shields, gowns, and gloves) but also for patients.

Recognizing all routes of infection generated in medical practice is important to reduce the risk of transmission to healthcare workers during bronchoscopy.[26] Taking off PPE inappropriately after bronchoscopy may lead to contact infection; therefore, appropriate education regarding correct wearing of PPE is required.[27–29] Moreover, ABPs during bronchoscopy can lead to the risk of environmental infection transmission through contact surfaces (e.g., endoscopic system).[30] As the e-mask could stop most ABPs at the front of the patient's mouth before they spread out to the environment, the e-mask may also be effective in reducing the environmental risk. However, further investigation is needed to determine whether the use of an e-mask during bronchoscopy can prevent the transmission of ABPs into the endoscopy room.

In our study, since there was a difference in the baseline SpO_2 and EtCO2 values before bronchoscopy, the occurrence of primary endpoint in the e-mask and control groups was not directly comparable. To compensate for the differences in the baseline SpO_2 and $EtCO_2$ values before bronchoscopy, a multivariate logistic analysis was performed to evaluate the factors affecting the incidence of patients requiring >5 L/min O_2 to maintain >90% SpO_2, and those with >45 mmHg $EtCO_2$ elevation. This analysis demonstrated that the use of the e-mask was not a significant factor influencing the deterioration of SpO_2, as shown in a previous report, which might have been due to biological compensation to maintain the SpO_2 by increased respiration and HR.[31] However, our study showed that the use of the e-mask was significantly associated with >45 mmHg $EtCO_2$ elevation. We considered that this rise in $EtCO_2$ was caused by the effects of re-inhalation of the exhaled air, in addition to the dead space and respiratory resistance.[32] Since this $EtCO_2$ elevation during bronchoscopy with the e-mask can be recovered to baseline levels after the procedure, we were optimistic about the use of the e-mask, except in patients with severe chronic obstructive pulmonary disease, who tend to develop narcosis.

High medical costs, lack of PPE including N95 masks, and a smaller number of intensive care unit beds and ventilators ultimately exposed the limitations in patient care during the COVID-19 pandemic.[33] Therefore, to develop new devices for the prevention of infectious diseases such as COVID-19, the following criteria should be met: cost-effectiveness, disposability, ease of use, and user-friendliness. N95 masks protect healthcare workers as PPE, while e-masks are for patients undergoing bronchoscopy. It is true that a slit in several masks (e.g., N95 mask, Hudson oxygen mask) other than surgical mask can be used as a replacement for e-mask, but the cost is too high to use these masks in routine bronchoscopy. Moreover, handmade creation is unsanitary and cumbersome, and the size of the slit differs each time, making it difficult to determine the accurate protective effect. In

terms of cost-effectiveness, e-mask made up based on surgical mask seems to be reasonable as it is mass-produced through use of the ordinary surgical-mask production lines, inexpensive, clean, and disposable, which enables its routine use in the clinic.

This study had several limitations. First, this was a single-center study and not a randomized trial. Therefore, even with propensity score matching, it was difficult to completely eliminate the clinical differences in the baseline characteristics. Second, we excluded patients with respiratory failure, history of CO_2 narcosis, and stage ≥2 chronic obstructive pulmonary disease. The safety of the e-mask in these patients is unknown. Further studies should be conducted to address these limitations.

In conclusion, the e-mask provided reasonable protection against respiratory ABPs with no significant increase in complications, although the $EtCO_2$ elevation should be considered. The e-mask should be equipped as a standard precaution during bronchoscopy not just during the COVID-19 pandemic, but also after it.

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CONFLICT OF INTEREST: None declared

DATA AVAILABILITY STATEMENT:

The data that support the findings of this study are available from the corresponding author upon reasonable request.

HUMAN ETHICS APPROVAL DECLARATION:

All clinical studies were reviewed and approved by the Nagoya University Ethical Review Committee (approval number, 2020-0127, 2020-0351). Written informed consent was obtained from the patient before performing bronchoscopy.

Clinical trial registration: UMIN000043050 at https://www.umin.ac.jp/ctr/

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Table 1 Baseline characteristics and safety profile in e-mask and control groups

	Before matching			After matching		
	E-mask group (n = 52)	Control group (n = 105)	*P* value	E-mask group (n = 52)	Control group (n = 40)	*P* value
Age in years, median (range)	71 (36–86)	70 (19–88)	0.757	71 (36–86)	72 (31–86)	0.942
Sex, male, n (%)	30 (57.7)	64 (61)	0.695	30 (57.7)	21 (52.5)	0.619
Smoking status, former/current, n (%)	36 (69.2)	42 (40)	< 0.001	36 (69.2)	23 (57.5)	0.245
FEV_1, L, median (range)	2.3 (0.9–4.1)	1.9 (0.9–4.3)	0.328	2.3 (0.9–4.1)	1.8 (0.9–4.2)	0.172
FEV_1/FVC, %, median (range)	71.7 (50.6–92)	69.7 (41.8–94.8)	0.250	71.7 (50.6–92)	69.4 (41.8–94.8)	0.332
FEV_1, percent predicted, %, median (range)	89.2 (36.3–122.6)	96.8 (37.4–153)	0.008	89.2 (36.3–122.6)	86.1 (37.4–142.3)	0.811
VC, percent predicted, %, median (range)	96.6 (54.9–135)	109.6 (55.8–168.8)	0.001	96.6 (65.1–128.5)	97.2 (55.8–128.5)	0.581

SpO_2, %, median (range)						
Baseline	99 (92–100)	96 (83–99)	< 0.001	99 (92–100)	95 (89–99)	< 0.001
Minimum	94 (79–100)	91 (60–98)	0.001	93.5 (79–99)	90 (60–95)	0.001
Delta	− 5 (−19–0)	− 4 (− 34–1)	0.231	− 5 (− 19–− 1)	− 4 (− 34–0)	0.624
$EtCO_2$, mmHg, median (range)						
Baseline	28 (7–59)	32 (3–44)	0.104	29 (7–43)	32 (12–43)	0.043
Maximum	42 (24–66)	38 (9–50)	< 0.001	42 (24–66)	37 (19–47)	0.001
Delta	13.5 (− 1–42)	4 (− 11–40)	< 0.001	14 (− 1–42)	3.5 (0–18)	< 0.001
Blood pressure, mmHg, median (range)						
Baseline	164 (94–216)	151 (98–220)	0.024	164 (94–216)	147 (98–220)	0.100
Maximum	201 (125–265)	172 (99–258)	< 0.001	203 (125–265)	172 (99–249)	0.001
Delta	34	16	< 0.001	35.5	16 (−	< 0.001

	(0–103)	(29–96)		(1–103)	7–90)	
Heart rate, /min, median (range),						
Baseline	81 (49–140)	84 (53–124)	0.682	81 (49–140)	84 (65–124)	0.196
Maximum	115 (71–149)	103 (61–151)	< 0.001	115 (71–149)	102 (76–151)	< 0.001
Delta	30 (0–71)	18 (7–61)	< 0.001	31 (0–71)	16 (5–61)	< 0.001
Maximum oxygen supplementation, L/min, median (range),	2 (2–8)	2 (1–10)	0.311	2 (2–8)	2 (2–10)	0.306
Examination time, min, median (range)	29 (5–79)	39 (4–128)	0.024	29 (5–79)	44.5 (4–85)	0.024
Midazolam dose, mg, median (range)	3.9 (1.5–10)	5.3 (1.7–19.5)	0.001	3.9 (1.5–10)	5.5 (1.7–12)	0.004
Procedures, n (%)			0.316			0.221
Only endobronchial observation	5 (9.6)	6 (5.7)		5 (9.6)	2 (5)	

Any procedures including BAL	8 (15.4)	25 (23.8)		8 (15.4)	11 (27.5)	
Biopsy/EBUS-TBNA without BAL	39 (75.0)	74 (70.5)		39 (75.0)	27 (67.5)	
Complications, n (%)	4 (7.7)	4 (3.8)	0.627	3 (5.8)	1 (2.5)	0.395

E-mask, endoscopic mask; FEV_1, forced expiratory volume; FVC, forced vital capacity; VC, vital capacity; SpO_2, saturation of percutaneous oxygen; $EtCO_2$, end-tidal carbon dioxide, BAL; bronchoalveolar lavage; EBUS-TBNA, endobronchial ultrasound-transbronchial needle aspiration

Table 2. Logistic regression analysis of factors affecting the occurrence of patients who required >5 L/min O2 to maintain >90% SpO_2 after matching

Variables		Multivariate OR (95% CI)	*P* value
Age	Continuous		0.398
Sex	Male		0.694
	Female	1 (ref)	
Smoking status	Former/current		0.568
	never	1 (ref)	
SpO_2 at baseline	Continuous	0.817 (0.682–0.978)	0.028
Examination time	Continuous		0.309
Midazolam dose	Continuous		0.753
Procedures			0.329
	Only observation		0.948
	Any procedures including BAL	-	0.189
	Biopsy/ EBUS-TBNA without BAL	1 (ref)	
E-mask	With		0.959
	Without	1 (ref)	
FEV_1/FVC	Continuous		0.948
VC, percent predicted	Continuous		0.609

O2, oxygen, SpO_2, saturation of percutaneous oxygen; OR, odds ratio; CI, confidence intervals; BAL, bronchoalveolar lavage; EBUS-TBNA, endobronchial ultrasound-transbronchial needle aspiration; E-mask, endoscopic mask; FEV_1, forced expiratory volume; FVC, forced vital capacity; VC, vital capacity

Table 3. Logistic regression analysis of factors affecting the incidence of patients with >45 mmHg $EtCO_2$ elevation after matching

Variables		Multivariate OR (95% CI)	*P* value
Age	Continuous		0.904
Sex	Male		0.672
	Female	1 (ref)	
Smoking status	Former/current	3.976 (1.251–12.636)	0.019
	Never	1 (ref)	
Baseline $EtCO_2$	Continuous		0.249
Examination time	Continuous		0.339
Midazolam dose	Continuous		0.061
Procedures			0.245
	Only observation		0.185
	with BAL	-	0.113
	Biopsy/EBUS-TBNA without BAL	1 (ref)	
E-mask	With	4.323 (1.190–15.7)	0.026
	Without	1 (ref)	
FEV_1/FVC	Continuous		0.612
VC, percent predicted	Continuous		0.639

$EtCO_2$, end-tidal carbon dioxide; OR, odds ratio; CI, confidence intervals; BAL, bronchoalveolar lavage; EBUS-TBNA, endobronchial ultrasound-transbronchial needle

aspiration; E-mask, endoscopic mask; FEV_1, forced expiratory volume; FVC, forced vital capacity; VC, vital capacity

FIGURE LEGEND:

Figure 1- Scheme of the new "e-mask", and visibility during bronchoscopy with or without the e-mask

a. Scheme of the e-mask (left). The mask had a 10-mm slit in the center for insertion of the fiberscope and a 6-mm slit on both sides for the suction tube (right). **b**. Comparative appearance of the e-mask and common surgical mask. **c.** The slit remains closed unless the bronchoscope is inserted. **d.** Visibility in bronchoscopy with or without the e-mask.

Figure 2- Evaluation of the effectiveness of the e-mask in preventing airborne particles

a. Scheme of the acrylic box for visualization of the airborne particles during spraying. To quantify the scattered airborne particles inside the box, we put black papers as indicated. **b.** Visualization of the sprayed red paint with or without the e-mask. The video image is showed in Supplementary Video 1a–1d. **c.** Fluorescent-green image on the black paper inside the acrylic box with or without the e-mask. **d.** Quantification of the fluorescent-green images on the black paper inside the acrylic box with or without the e-mask (n = 3; above, $P = 0.0202$; left, $P < 0.0001$; right, $P = 0.0122$; head, $P = 0.0019$). **e.** Visualization experiment of airborne particles using an ultra-high-sensitive camera (ViEST system, SHIN-NIHON-Kucho, Tokyo, Japan). The light source was a 400–410-nm wavelength LED. The ViEST system is aligned with the target (airborne particles), aimed above the nose and mouth. **f.** The ViEST system images of splashes during coughing with or without the e-mask. The mask can prevent the splashes and droplets. Bar is 10 cm. See Supplementary Video 2. **g.** Quantification of the airborne particles via video analysis of the images of the splashes during coughing with or without the e-mask. (n = 3, $P = 0.011$). **h.** Time course of the airborne particles' volume in three experiments with or without the e-mask. **i.** Direct counting of the airborne particles. The airborne particles 45 cm above the nose and mouth were counted. **j.** Quantification of the

airborne particles via direct counting with or without the e-mask (n = 12, $P < 0.0001$). **k.** Visualization experiment of the mist using the ViEST system. **l.** Ultra-high-sensitive camera (ViEST system) images of the mist with or without the e-mask. The e-mask almost prevents the mist. Bar is 10 cm. See Supplementary Video 3.

Figure 3-Simulation of the spread of small airborne particles with or without the e-mask

a. Appearance of the simulation settings with or without the e-mask. **b.** Simulation images of the aerosols (1 mm) with or without the e-mask. See Supplementary Video 4.

Figure1

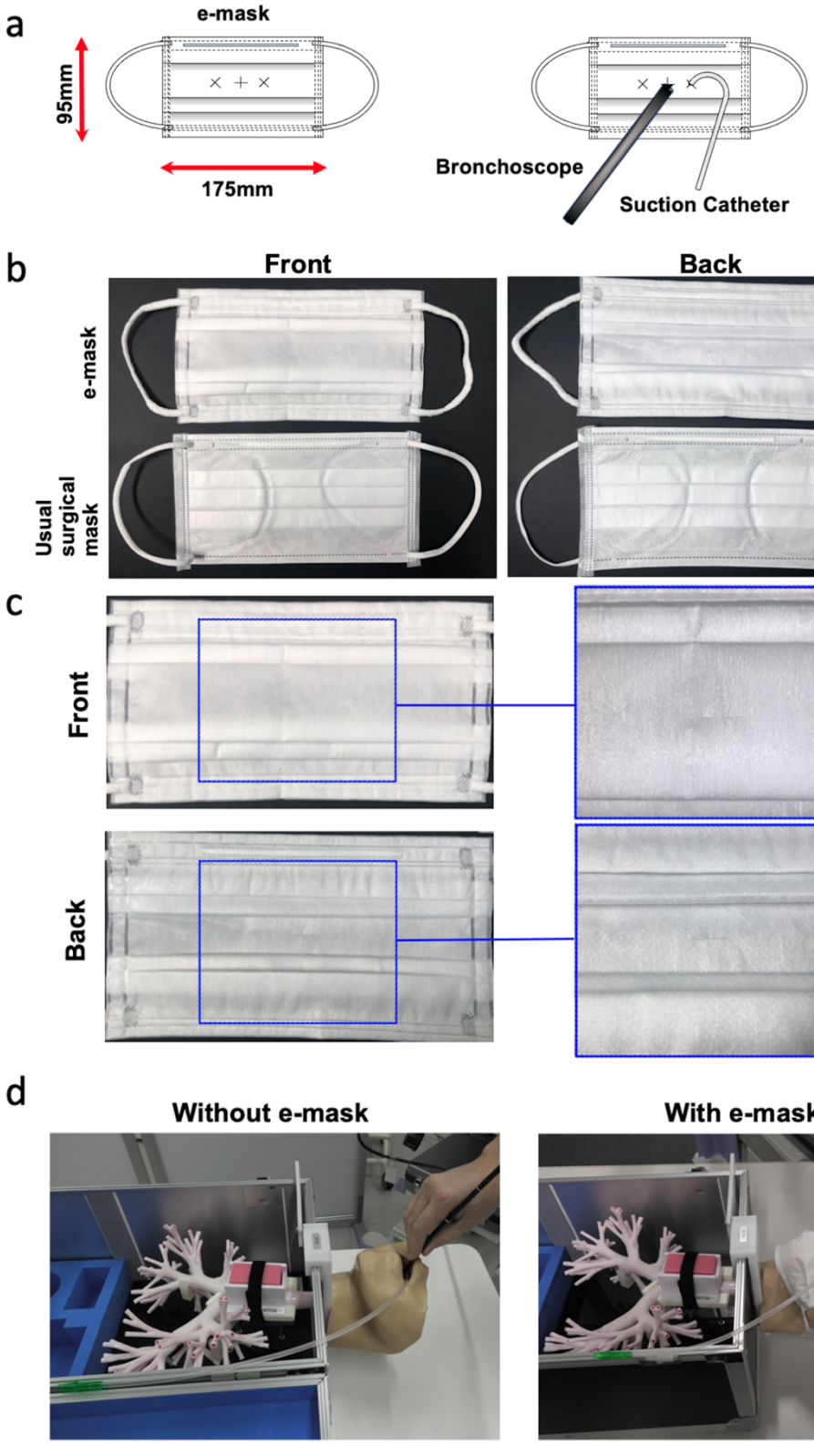

a
e-mask
95mm
175mm
Bronchoscope
Suction Catheter
b
Front
Back
e-mask
Usual surgical mask
c
Front
Back
d
Without e-mask
With e-mask

Figure2

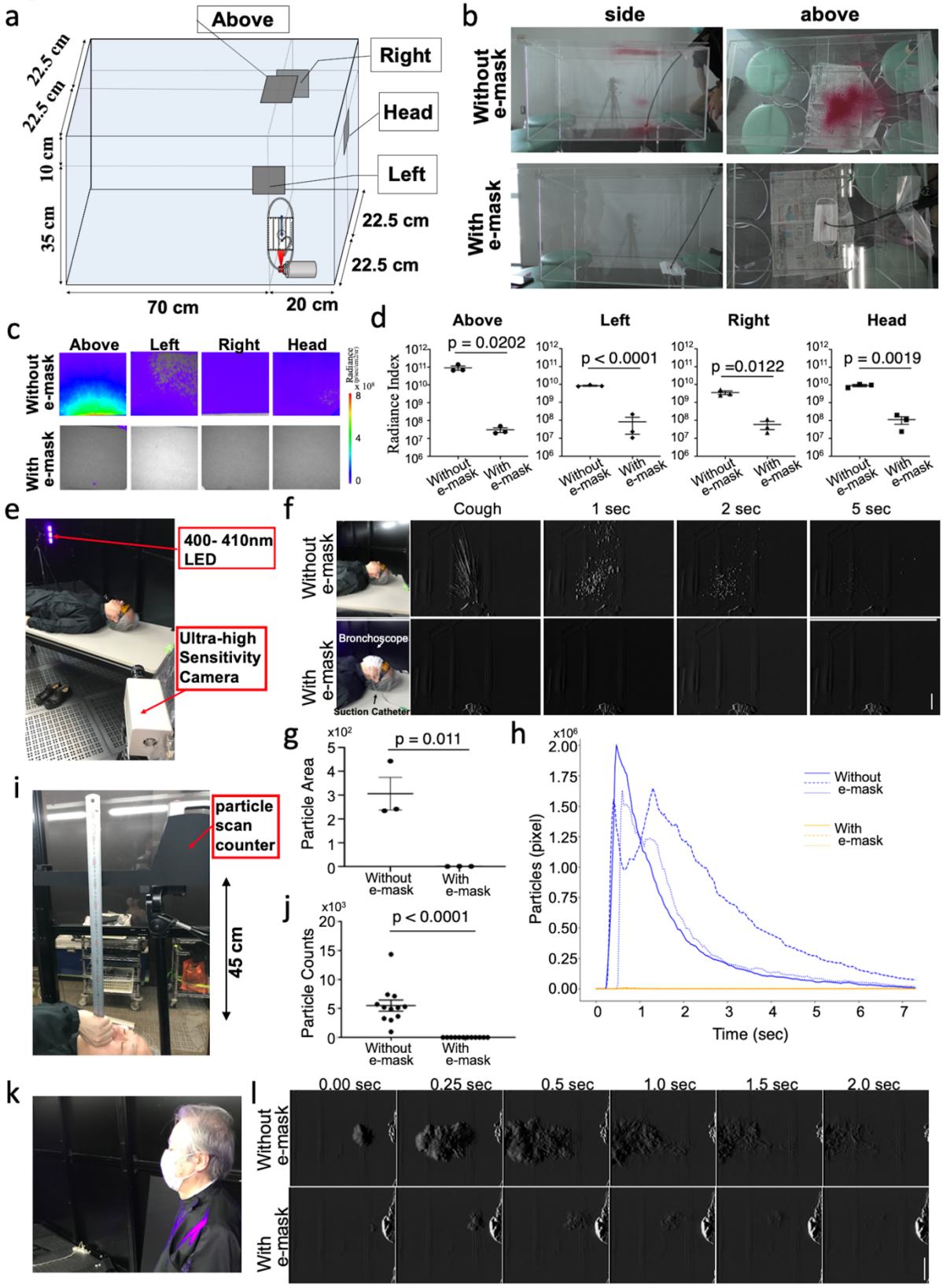
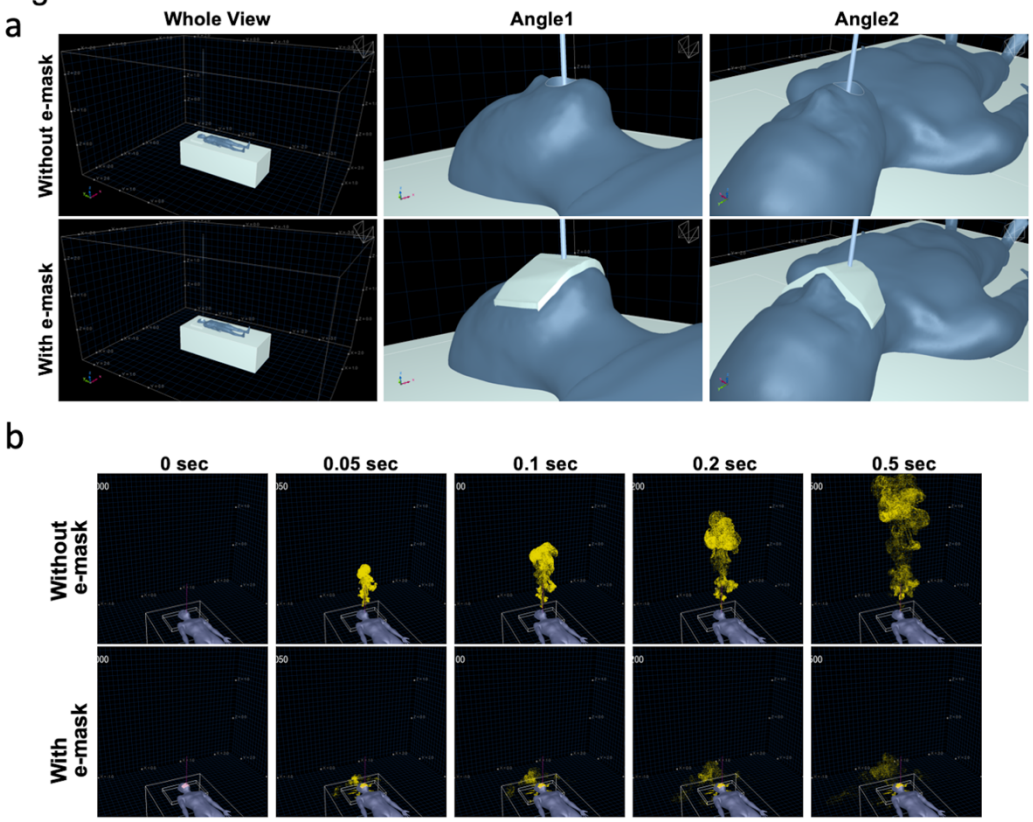

a
Above
Right
Head
Left
22.5 cm
22.5 cm
10 cm
35 cm
22.5 cm
22.5 cm
70 cm
20 cm
b
side
above
Without e-mask
With e-mask
c
Above
Left
Right
Head
Without e-mask
With e-mask
Radiance (p/s/cm²/sr)
x 10⁸
8
4
0
d
Above
Left
Right
Head
p = 0.0202
p < 0.0001
p =0.0122
p = 0.0019
Radiance Index
Without e-mask
With e-mask
e
400- 410nm LED
Ultra-high Sensitivity Camera
f
Cough
1 sec
2 sec
5 sec
Without e-mask
With e-mask
Bronchoscope
Suction Catheter
g
x10²
p = 0.011
Particle Area
Without e-mask
With e-mask
h
x10⁶
Without e-mask
With e-mask
Particles (pixel)
Time (sec)
i
particle scan counter
45 cm
j
x10³
p < 0.0001
Particle Counts
Without e-mask
With e-mask
k
l
0.00 sec
0.25 sec
0.5 sec
1.0 sec
1.5 sec
2.0 sec
Without e-mask
With e-mask

Figure3


a
Whole View
Angle1
Angle2
Without e-mask
With e-mask
b
0 sec
0.05 sec
0.1 sec
0.2 sec
0.5 sec
Without e-mask
With e-mask

SUPPORTING INFORMATION

TITLE: Prevention of droplet dispersal with "e-mask"; a new daily use endoscopic mask during bronchoscopy

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This supplement contains the following items:

Supplementary Methods

Supplementary Results

Supplementary Methods

Visualization experiments

Mask design

Similar to common surgical masks, this e-mask has a 3-layer structure; the two outer layers are non-woven fabrics, and the middle layer is an electrically charged filter that blocks 99% of the particles. The mask has a 10-mm cross-shaped slit (endoscope hole) in the center and X-shaped slits (catheter holes) on either side. The new mask was made by Suzuken Kenz (Suzuken Co., Ltd., Nagoya, Japan) and was named “e-mask” (based on “endoscopic mask”) for routine clinical use.

Acrylic box for visualization of airborne particles (ABPs) during spraying

The head and tail sides constitute the length; when viewed from the head side, the width constitute the right and left sides, and the lid is the top. A 4×3.5 cm hole was drilled into the center of the bottom, 20 cm from the head side. A bite-block was placed in the bottom hole to simulate the patient's mouth. The mask was fixed on top of the bite-block during the spray experiment. For the bronchoscope (1T-30, Olympus, Tokyo, Japan), we moved the top lid of the acrylic box, placed the bronchoscope inside, and passed the endoscope through the bottom hole via the mask/bite-block. The suction catheter was placed in the box as well, and the tip was passed through the bottom hole via the mask/bite block.

Visualization of the ABPs using ultra-high-sensitive camera

An ultra-high-sensitive camera and high-power light source (ViEST system, SHIN-NIHON-Kucho, Tokyo, Japan) was used to detect the generated droplets. The light source (parallel Eye D, SHIN-NIHON-Kucho) has a 400–410-nm LED peak wavelength. This system has a sensitivity that can be used to visualize airborne particles that are a minimum 80 nm in size.

Quantification of the ABPs using ultra-high-sensitive camera

After loading the videos in Matplotlib 3.2.2, OpenCV 4.3.0. and cropping them to exclude the participant's face and mask, up to 230 pixels from the right edge were removed. Furthermore, to remove the noise and background, an average image was created from the first 100 frames of the video and subtracted from all video frames. The video was divided into three sections at the time of coughing, and the average pixel value within each section was calculated.

Visualization of the airborne mist using ultra-high-sensitive camera

An ultra-high-sensitive camera and a high-power light source (ViEST system, SHIN-NIHON-Kucho, Tokyo, Japan) was used to detect the mist released from the mouth.

Simulation of the aerosol spread via air-fluid flow analysis

The simulation of the spread of aerosols was performed using the Cradle CFD/scFLOW software (MSC Software, Tokyo, Japan). An analysis of the non-constant turbulence was used (dt = 2e-5[sec/cycle]). Turbulence analysis method used was Large Eddy Simulation and subgrid-scale modeling (Wall-Adapting Local Eddy-viscosity model). The flow speed was set to 45 m/s (0–0.1 s) and decreased linearly to 0 m/s. The aerosol particles were determined to have a density of 1000 kg/m^3, a size of 1 μm, and generating 1×10^4 particles per 50 cycles. The initial velocity of the particles was set to 45 m/s. The pressure loss conditions due to the e-mask were set using the following formula: dP/dL [N/m^3] = $6 \times 10^6 \times$ flow speed. The gap between the nose and e-mask and between the cheek and e-mask were determined for the analysis.

Feasibility manikin study on the use of e-mask during bronchoscopy

A crossover study was performed to evaluate the operability of the bronchoscope with the e-mask. The primary endpoint was the duration of simple observation using bronchoscopy, and the secondary endpoint was the questionnaire score. The participating physicians were respiratory physicians (bronchoscopists) with at least 5 years of clinical experience, proficient in bronchoscopy, and able to provide free consent. All participating physicians provided signed informed consent for the study. To perform these tests, bronchoscopy was performed four times in total, twice with and without the e-mask on the bronchoscope (1T260; Olympus, Tokyo, Japan), in an alternating order with and without the e-mask. The simple observation duration was defined as the time taken for the bronchoscope to pass through the e-mask or oral cavity until all bronchial subsections were observed, and the bronchoscope was removed from the e-mask or oral cavity. After the examination, a questionnaire was used to score the following items: bronchoscope operability from the oral cavity to the glottis, operability after the glottis, and whether bronchoscopists would prefer to use the e-mask for patients in clinical practice (using a scale of 0–5, with 5 corresponding to not wanting to use the e-mask).

Patient application of e-mask use during bronchoscopy

We prospectively enrolled patients who underwent flexible bronchoscopy using the e-mask (e-mask group) between November 1, 2020 and February 28, 2021. For the inclusion and exclusion criteria, see e-Figure 1. We compared the e-mask group with consecutive patients who underwent bronchoscopy without the e-mask (control group) between April 1, 2011 and September 30, 2011. The inclusion and exclusion criteria for the control group were the same as that for the e-mask group.

Procedures

Spirometry was performed a day prior to the bronchoscopy. For the midazolam loading dose for sedation during bronchoscopy in the two groups, see e-Figure 1. Oxygen (O2) supplementation (2–4 L/min) was performed in all patients before bronchoscopy, and oxygen flow was increased to maintain >90% Saturation of percutaneous oxygen (SpO_2).

Study endpoints

The primary endpoint was the incidence of respiratory adverse events [patients who required >5L/min O_2 to maintain >90% SpO_2, and those with >45 mmHg end-tidal carbon dioxide ($EtCO_2$) elevation] during bronchoscopy in the two groups. The secondary endpoint was the presence or absence of bronchoscopic complications that required prolonged admission (e.g., severe bleeding, pneumothorax requiring thoracic drainage) in the two groups.

Statistical analysis

Patient application of e-mask use during bronchoscopy

We calculated the basic statistics (maximum–minimum values, median, and range) for all items obtained as continuous values. Data are presented as the median (range). Statistical analysis of continuous data was performed using the Mann–Whitney U test and Wilcoxon signed-rank test, and that for categorical variables was performed using the Pearson's chi-square test. Propensity score matching was performed to reduce the clinical differences of the baseline characteristics before the patient was on the examination table between the e-mask group and historical cohort. Propensity scores were generated using logistic regression, which included smoking status and vital capacity (predicted percentage). Propensity score matching was then performed using nearest neighbour matching without replacement and one-to-one pair matching with a calliper width of 0.05. Additionally, multiple logistic regression analysis was performed to correct the differences in SpO_2 and $EtCO_2$ at baseline between the e-mask

and control groups, and to identify factors associated with the incidence of the primary endpoint. The variables analysed in relation to the incidence of patients requiring >5 L/min oxygen to maintain >90% oxygen saturation were SpO2 at baseline and factors of a) to i), as described below, while those analysed in relation to the incidence of patients with >45 mmHg EtCO2 elevation were EtCO2 at baseline and the same factors of a) to i), as follows: a) age, b) sex (male or female), c) smoking (former/current smoker or never smoker), d) examination time, e) midazolam dose, f) bronchoscopic procedure (only observation, any procedures including bronchoalveolar lavage, biopsy/ endobronchial ultrasound-transbronchial needle aspiration without bronchoalveolar lavage), g) the use of the e-mask (with the e-mask or without the e-mask), h) forced expiratory volume/forced vital capacity, and i) vital capacity, percent predicted.

Figure Legends

e-Figure 1. Inclusion and exclusion criteria for patients who underwent flexible bronchoscopy.

Supplementary Results

Feasibility manikin study on the use of the e-mask during bronchoscopy

e-Figure 2. Simple observation during bronchoscopy with or without the e-mask (n = 33, *P* = 0.796). The results of the questionnaire filled in by the bronchoscopists (respiratory physicians) who participated in this study. Operability from the oral cavity to the glottis, operability after the glottis, and whether bronchoscopists would like to use the new mask for patients in clinical practice. We measured the duration for simple observation of the bronchus via bronchoscopy. The duration for simple observation with the e-mask was not significantly different from that without the e-mask (e-Figure 2a). The results of the questionnaire filled in by the bronchoscopists who participated in this study demonstrated that almost all bronchoscopists experienced no remarkable stress with the use of the e-mask, and they would prefer to use the e-mask during bronchoscopy (e-Figure 2b).

Changes in SpO_2, $EtCO_2$, systolic blood pressure (SBP), heart rate (HR), and respiratory rate (RR) in the e-mask group during bronchoscopy

e-Figure 3. Changes in SpO_2, $EtCO_2$, SBP, HR, and RR during bronchoscopy in the e-mask group were presented. The minimum SpO_2 value was significantly lower than the baseline value. Moreover, the maximum $EtCO_2$, SBP, HR, and RR values were significantly higher than the baseline values. The $EtCO_2$, SBP, and RR at bronchoscopy completion were not significantly different from those at baseline, although the SpO_2 and HR were significantly different from the baseline values.

e-Figure 1

Inclusion and exclusion criteria

- Inclusion criteria: patients aged ≥ 15 years with normal respiratory function or stage 1 chronic obstructive pulmonary disease and with resting oxygen saturation of 90% or more (room air).
- Exclusion criteria: patients who cannot keep rest during bronchoscopy and had a history of carbon dioxide narcosis.

Sedation protocol of midazolam

- E-mask group

a) Patients aged ≤70 years received intravenous administration of midazolam at a dose of 0.06–0.075 mg/kg, immediately before initiating bronchoscopy. A supplementary dose (half of initial dose) was administered at an interval of at least 10 min, if necessary.

b) Patients aged 71–84 years received intravenous administration of midazolam at a dose of 0.04–0.05 mg/kg, immediately before initiating bronchoscopy. A supplementary dose (half of initial dose) was administered at an interval of at least 10 min, if necessary.

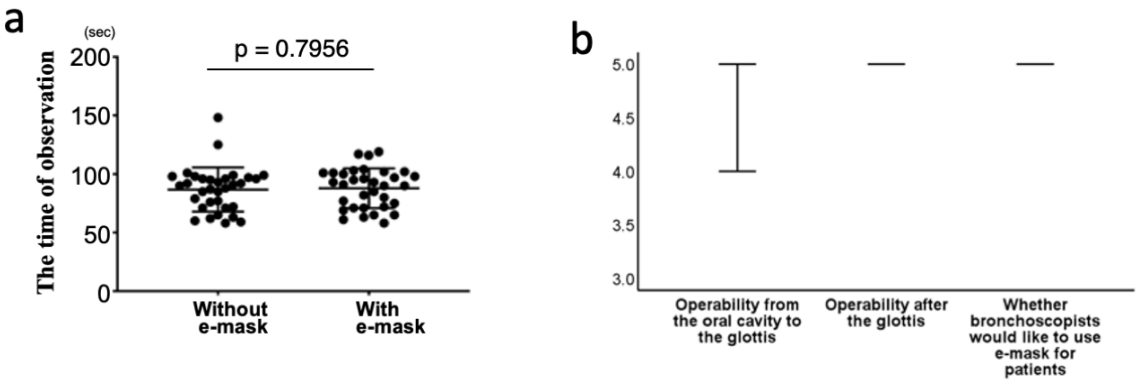
c) Patients aged ≥85 years received intravenous administration of midazolam at a dose of 0.04–0.05 mg/kg, immediately before initiating bronchoscopy. However, no supplementary doses were administered during the procedure.

- Control group

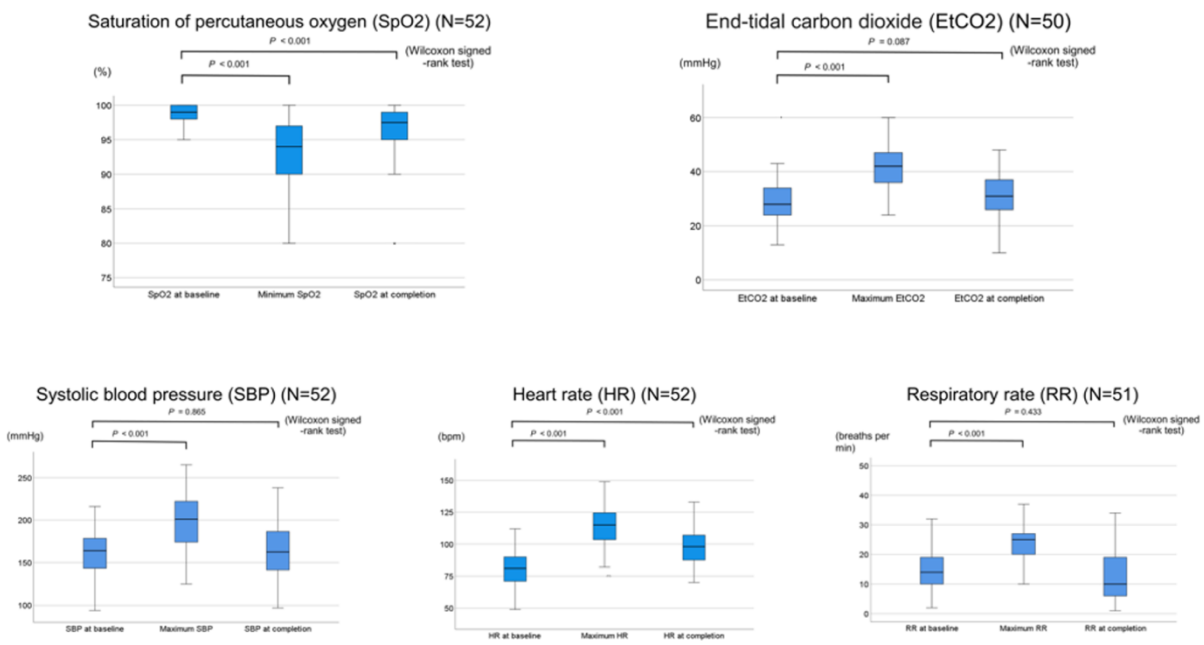
a) The loading dose of midazolam was 0.075mg/kg for men ≤65 years old and women ≤70 years

b) The loading dose of midazolam was 0.05mg/kg for men ≥66 years and women ≥71 years, with subsequent doses of one-half the loading dose to be administered every 20min.

e-Figure 2



e-Figure 3



Supplementary Video1

Visualization of the sprayed red paint with or without the e-mask.

(a) spray without e-mask (b) appearance after the spray without e-mask

(c) spray with e-mask (d) appearance after the spray with e-mask

Supplementary Video2

The ViEST system video images of splashes during coughing with or without the e-mask.

Supplementary Video3

Ultra-high-sensitive camera (ViEST system) images of the mist with or without the e-mask.

Supplementary Video4

Simulation of the spread of air flow with or without the e-mask.