Full title: Development of a novel lung-stabilizing device for VATS procedures

Running head: Development of a novel lung stabilizer

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Funding:

This work was supported by Fuji Systems Corp., Tokyo, Japan.

Abstract

Background

The use of video-assisted thoracoscopic surgery (VATS) has become more widespread in recent years. These procedures require the insertion of specialized devices into the thoracic cavity via access ports to provide a clear field of vision for surgery. Conventional devices such as cotton-tipped applicators and graspers afford a limited view and may injure fragile lung tissue. The aim of this study was to develop a novel lung-stabilizing device for VATS that provides a good surgical field of vision without causing lung injury.

Methods

We developed a novel suction-based lung-stabilizing device equipped with three hemispheric 20-mm-diameter silicon suckers. The utility and safety of the novel device were evaluated using a resected pig lung and canine models. Additionally, in order to assess potential organ damage arising from the use of the novel device, canine lung parenchyma and pleura were macroscopically and microscopically examined after the suction-based device had been continuously applied under negative pressure conditions of -400 mmHg and -540 mmHg for one hour.

Results

Using the novel device, we performed lobectomies in the resected pig lung and VATS in canine models to assess its utility. The device demonstrated sufficient power to stabilize the lung and provide a clear field of vision during surgery, and enabled us to perform VATS lobectomies more easily than when using conventional stabilizing forceps. Assessment of the dogs' lungs immediately after detaching the novel device revealed no complications such as hemorrhage, air leaks, and bullae formation. Pathological examination performed seven days later also showed no substantial damage, except for a small impression in the pleura and parenchyma of the surface layer where the device had contacted the lung tissue.

Conclusions

Although further validation studies in clinical settings are required, our study indicates that the novel lung-stabilizing device has useful applications in VATS procedures.

Key words

Video-assisted thoracoscopic surgery, novel device, lung-stabilizing device, sucker, organ injury, non-invasive surgery

Introduction

With a growing emphasis on non-invasive surgery, the application of video-assisted thoracoscopic surgery (VATS) has become more widespread in recent years. However, VATS poses certain unique challenges due to the slippery and flexible characteristics of the lung as it expands and contracts. In addition, surgeons must work in a limited space within the rigid thoracic cage filled with the expanding and contracting lung if there are problems with one-lung ventilation.

It is necessary to push aside or grasp the lung to stabilize the organ and provide an adequate view during VATS procedures, but conventional devices such as cotton-tipped medical applicators and graspers may damage the fragile lung tissue. In addition, the limited view can affect surgical performance. At present, there are several surgical devices that use vacuum systems, including the OCTOPUS™ tissue stabilizer (Medtronic, Minneapolis, MN, USA), the Starfish™ heart positioner (Medtronic, Minneapolis, MN, USA), and the OVALEAD™ ovary stabilizer (Fuji Systems Corp., Tokyo, Japan). However, there are currently no specific devices for lung retraction, and we hypothesized that a suction-based device may have applications for stabilizing lungs during VATS procedures. We aimed to develop a novel suction device for endoscopic surgery that provides a good surgical view without causing lung injury.

Materials and Methods

Animals and surgical procedures

We planned and performed animal experiments to assess the utility and safety of the novel device. In this study, we first used a resected pig lung followed by canine models. The experiments were approved by the Kyoto University Animal Experimentation Committee, and all surgical procedures and euthanasia were performed in accordance with the National Institutes of Health animal care guidelines.

We purchased a resected pig lung from a local slaughterhouse, and used it to assess the power of the novel device. The weight of the lung lobes ranged from 80 g to 280 g, and their physical properties were considered similar to those of a human lung.

Canine models were then used to evaluate the application of the device in VATS procedures. A total of seven adult dogs (beagles) weighing approximately 6.0 kg to 10.0 kg were used in this study. After premedication with atropine sulfate at 0.03 mg/kg, the dogs were anesthetized with an intramuscular injection of ketamine hydrochloride at 15 mg/kg and xylazine at 7 mg/kg.

The novel device

The OVALEAD™ device is an endoscopic instrument designed to stabilize the ovary, and is equipped with a hemispheric silicon sucker that is 20 mm in diameter (Figure 1a). We first attempted to perform a lobectomy on the resected pig lung using the unmodified device at a negative pressure of -400 mmHg. Next, we modified the OVALEAD™ device such that it was equipped with three suckers in one unit to provide more power to securely grip the lung tissue (Figure 1b). There is a 2-mm vacuum port in the center of each sucker, and 1-mm-diameter tubes are introduced through these ports. These tubes are gathered into a single duct at the joint of the suckers and the built-in metal shaft. The device with three suckers was referred to as the “novel device”, and was used to perform a lobectomy on the resected pig lung at a negative pressure of -400 mmHg.

Utility assessment of the novel device for canine VATS

Using four dogs, we performed eight cases of VATS lower lobectomies (both sides of each dog) to assess the utility of the novel device. Half of the cases were performed

using conventional lung forceps, and were designated the control cases. The remaining four lobectomies were performed using the novel device, and were designated the experimental cases. The experiments were equally allocated to the left and right sides in both the control and experimental groups.

In all cases, the animals were placed in the left or right decubitus position before VATS lobectomy was performed. A 1.5-cm camera port was created in the tenth intercostal space and a 7-cm utility incision was made in the sixth intercostal space. All surgeries were performed by two surgeons who alternated their roles (primary surgeon or assistant) for each procedure.

We assessed the following outcome measures to evaluate the utility of the novel device: surgical time, number of interruptions during surgery, organ damage, and addition of an assist port. Surgical time was defined as the duration from the insertion of a device into the thoracic cavity until the completion of the lobectomy, and an interruption during surgery was defined as a situation where the scope was removed from the thoracic cavity due to poor visibility.

Lung damage assessment

Damage to the lung was assessed independently from the utility assessment of the novel device. To assess lung damage, a single 20-mm-diameter sucker was continuously applied for one hour to the surfaces of dogs' lungs at a negative pressure of either -400 mmHg or -540 mmHg at 11 sites; six sites were subjected to a negative pressure of -40 0 mmHg and five sites were subjected to a negative pressure of -540 mmHg. Negative pressure was measured using an electronic manometer (Copal Electronics Corp., Tokyo, Japan). As controls, conventional lung forceps were similarly applied to dogs' lungs for one hour at 12 sites. We used a total of five dogs to assess lung damage.

Figure 2a shows the actual experimental conditions at -540 mmHg. The lungs were macroscopically examined immediately after surgery and again seven days later. After the second examination, we performed lobectomy for each case. The entire resected lobe for each lung was re-inflated with 10% formalin and immersed in the same solution. After fixation, samples were excised, embedded in paraffin, sectioned, and subjected to either hematoxylin-eosin staining (H-E stain) or Elastica-Masson staining (E-M stain). The stained sections were microscopically examined using an optical microscope.

Lung damage was assessed using the following outcome measures: alveolar deformation, pleural thickening, pleural hemorrhage, parenchymal hemorrhage, and

stromal hypertrophy. The degree of alveolar deformation was assessed using an index ranging from Grade 0 to Grade 3. Specifically, Grade 3 involved overall atelectasis (Figures 3a and 3b), Grade 2 involved the deformation of deep lung parenchyma (Figures 3c and 3d), Grade 1 involved the deformation of only the superficial lung parenchyma layer adjacent to the pleura (Figures 4a and 4b), and Grade 0 involved no alveolar deformation (Figures 4c and 4d).

The other outcomes were divided into two categories, where a value of 1 indicated the presence of the outcome measure and a value of 0 indicated its absence. Using these assigned numerical values, we also calculated the total number of points in each group to represent the aggregate score for lung damage. This scoring method was developed and implemented by two pathologists and three surgeons.

Statistical analysis

The outcome measures were examined using univariate analyses: the chi-square test was used for categorical variables and the *t*-test was used to compare the total number of points for lung damage. In addition, we also divided the cases subjected to the suction-based device into two groups according to the degree of negative pressure (-400

mmHg and -540 mmHg), and comparatively examined the outcome measures. *P* values (two-sided) less than 0.05 were considered statistically significant. All statistical analyses were performed using JMP software version 11 (SAS Institute Inc. NC, USA).

Results

Utility assessment of the novel device using the resected pig lung

The utility of the novel device was first assessed *ex vivo* by conducting lobectomies in a resected pig lung. Initially, we found that the unmodified device lacked the power to lift up the heavy lobes of the pig lung. However, the novel device (with three suckers) was able to securely lift up the lung lobes under conditions of -400 mmHg, which would stabilize the lung and provide a clear field of vision for surgeons, as shown in the **video1**.

Utility assessment of the novel device for canine VATS

The novel device was also found to have useful applications in the canine VATS lobectomies, as shown in the **video2**. The results of the outcome measures of utility for the canine VATS lobectomy cases are summarized in **Table 1**. The results showed that

there were significantly fewer interruptions during surgery in the novel device group than in the conventional lung forceps group. Furthermore, the novel device demonstrated better performance than the conventional lung forceps in the other outcome measures, although the differences were not statistically significant. The use of the novel device contributed to substantially shorter surgical times (32 min vs 22 min), did not result in any intraoperative and postoperative macroscopic damage to the resected lung, and did not require the addition of an assist port.

Lung damage assessment

Macroscopically, we observed no complications (such as hemorrhage, air leaks, and bullae formation) immediately after detaching the single-sucker device for the two different suction conditions (-400 mmHg and -540 mmHg for one hour). Although the device left marks on the lung surface immediately after detachment (Figure 2b), these marks generally disappeared following several minutes of ventilation, with the exception of a small amount of congestion (Figure 2c). Subsequent macroscopic examination conducted seven days after surgery revealed no tissue damage (Figure 2d).

Pathological examination of the E-M and H-E stained sections showed several

occurrences of alveolar deformation and fibroblast formation in the deep lung parenchyma for the conventional lung forceps cases (Figure 3). In contrast, there was no evidence of alveolar deformation or fibroblast formation in the deep lung parenchyma for cases subjected to the suction-based device (Figure 4); however, several of these cases showed signs of superficial damage in the lung parenchyma adjacent to the pleura (Figures 4a and 4b) that did not extend more than 500 μm below the elastic pleural plate.

In all cases, pleural thickening was observed in the areas that were in contact with the sucker or had been grasped by conventional lung forceps. Based on our scoring method, the degree of deformation in the lung parenchyma was generally lower in the suction-based device cases than in the conventional lung forceps cases.

The results of the univariate analysis of lung damage in the suction-based device group and lung forceps group are summarized in Table 2. A significantly higher incidence of alveolar deformation was detected in the lung forceps group. In addition, stromal hypertrophy was more frequent in the lung forceps group, but this difference was not statistically significant.

The univariate analysis results of lung damage in the two different groups of suction-based device cases (-400 mmHg and -540 mmHg) are summarized in Table 3.

There were no significant differences between the two groups for all outcome measures.

Discussion

At present, there are several surgical devices that use vacuum systems, such as the OCTOPUS™ tissue stabilizer, the Starfish™ heart positioner, and the OVALEAD™ ovary stabilizer. The Starfish™ and OCTOPUS™ devices are used in cardiovascular surgery, and enable off-pump coronary artery bypass grafting to be performed in a safe and efficacious manner. [1-4]

In particular, the derivative Starfish™ NS device has been used in minimally invasive cardiac surgery for over a decade. However, there are currently no suction-based stabilizing devices available for general thoracic surgery. A previous case report has described using the Starfish™ device in surgery for mediastinal tumors [5], but to the best of our knowledge, there have been no reports about using these devices for lung surgeries. We considered that it would be difficult to apply these devices in their original form to the fragile lung tissue, and that modifications are needed before their application to VATS procedures. During these procedures, surgeons must make frequent and prompt changes to the lung position, and care must be taken not to damage the

organ. We postulated that the OVALEAD™ device may be able to fulfill the criteria needed for VATS procedures.

Before evaluation of the novel device, we assessed the unmodified OVALEAD™ in a resected pig lung using a negative pressure of -400 mmHg. However, the device failed to adequately stabilize the lung and was easily detached from the lung surface. As a result, the unmodified device was determined to be underpowered for lung surgery. The softness and flexibility of lung tissue and the limited insert angle of instruments in VATS procedures may have resulted in the formation of gaps between the lung and sucker that caused the unstable attachment.

Although we first attempted to provide more suction power by increasing the diameter of the sucker from 20 mm to 35 mm, this modification proved ineffective as the greater contact area between the sucker and lung surface was more likely to result in a gap. As an alternate approach, we increased the number of suckers to achieve sufficient suction power for lung stabilization. We also designed the suction tubes to have thin 1-mm diameters to prevent the simultaneous release of negative pressure between the lung surface and sucker even if one of the suckers became detached from the lung. This improvement provided sufficient traction of the lung tissue, which facilitated a clear view of vision and allowed surgery to be performed more easily in the

canine models.

In the procedures using canine VATS, the use of the novel device made it easier for us to operate on hilar lesions because the device was able to lift up the lobes and provide an unobstructed view for surgery, thereby contributing to substantially shorter surgical times, fewer interruptions in surgery, and a reduction in the need for assist ports. In addition, we did not need to frequently change the lung position during surgery when using the novel device due to the clear field of vision that it provided.

Although we were obliged to make a 7-cm long utility incision to use the novel device in canine experiments due to the flat and small thoracic cavity, a 1.5-cm incision would be sufficient for inserting the novel device into the thorax if folded. We have also further modified the device such that it could be used via a 5-mm port by separating the suckers from the shaft and connecting them after insertion in the thorax.

We anticipated the possibility that applying the novel device to the lung surface may damage the tissue. Furthermore, little was known about the comparative damage to lung tissue between conventional lung forceps and the novel device. Based on our macroscopic and histologic examination for lung damage, we found that the conventional lung forceps tended to cause irreversible damage such as atelectasis or fibroblast formation. In contrast, the novel device sometimes caused minor alveolar

deformation that was limited to the superficial layer of the lung parenchyma. In this respect, the novel device was less traumatic than the forceps.

The reasons for using -400 mmHg and -540 mmHg as indicators to assess organ damage in this study were that -400 mmHg is the standard pressure for the OCTOPUS™ and Starfish™ devices, and -540 mmHg is the maximum negative pressure that is generally used in the operation room. (JIST 7101: 2014) Our analysis found no significant difference in lung damage between these two levels of negative pressure. At present, we consider the maximum permissible negative pressure for lung tissue to be -540 mmHg.

To our knowledge, there are currently no published reports involving the assessment of complications arising from the use of negative pressure on biological tissue. We posit that negative pressure is less traumatic for lung tissue than the use of forceps due to the distinctive sponge-like characteristic of lung parenchyma. This characteristic may allow the countertraction of the lung to the suction device to be dispersed and distributed over the entire lobe, thereby suppressing damage to the lung tissue.

The novel device proposed here may have applications in lungs that do not require resection or are diseased, such as cases with chronic obstructive pulmonary

disease or interstitial pneumonia. Although validation is required for human subjects in clinical settings, the novel sucker device was found to be useful in VATS procedures in canine models.

Conclusions

The novel suction-based lung-stabilizing device was sufficiently powerful to manipulate lungs without causing tissue damage, and may therefore have useful applications in facilitating and simplifying VATS procedures.

Acknowledgements

We would like to express our appreciation to Messrs. Fumikazu Watanabe and Akihiro Asai of Fuji Systems Corporation (Tokyo, Japan) for supplying us with the device prototype.

Disclosures

Drs. Yusuke Muranishi, Toshihiko Sato, Yojiro Yutaka, Yasuto Sakaguchi, Teruya Komatsu, Akihiko Yoshizawa, Masahiro Hirata, Tatsuo Nakamura, and Hiroshi Date have no conflicts of interest or financial ties to disclose.

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Figure Legends

Figure 1. Devices used in this study

a) OVALEAD^{TM} device manufactured by Fuji Systems Corp., Tokyo, Japan.

b) The novel device equipped with three suckers at the end of the device. Each sucker has a diameter of 20 mm.

Figure 2. Macroscopic appearance of the lung surface during and after contact with the novel device

a) Experimental procedure during the assessment of lung damage. The device on the left is the 20-mm-diameter sucker, which was attached to the lung at a negative pressure of either -400 mmHg or -540 mmHg. The conventional lung forceps are shown on the right, and were used to grip the lung at a distance away from the sucker in each case. Both devices were attached to the lung for one hour before detachment and subsequent macroscopic examination.

b) Macroscopic appearance of the lung tissue immediately after detachment of the 20-mm-diameter sucker (attached at -540 mmHg for one hour). The sucker has left a mark.

c) Macroscopic appearance of the lung tissue described in Figure 2b after several

minutes of ventilation. The mark has noticeably diminished.

d) Macroscopic appearance of the lung tissue described in Figure 2b seven days after detachment of the sucker. Apart from a small scar, there was little sign of tissue damage.

Figure 3. Histologic examination of lung tissue samples seven days after detachment of the conventional lung forceps

a, b) Histologic changes were observed throughout the lung parenchyma after being grasped by conventional lung forceps for one hour. Pleural thickening and congestion, pleural hemorrhage, parenchymal hemorrhage, and stromal hypertrophy was detected. Atelectasis was detected in the lung parenchyma, and the alveolar deformation index was assessed to be Grade 3 in this sample. (a: Hematoxylin-eosin stain, magnification ×40; b: Elastica-Masson stain, magnification ×40)

c, d) Alveolar deformation was detected in the deep lung parenchyma after being grasped by conventional lung forceps for one hour. The alveolar deformation index was assessed to be Grade 2 in this sample. (c: Hematoxylin-eosin stain, magnification ×40; d: Elastica-Masson stain, magnification ×40)

Figure 4. Histological examination of lung tissue samples seven days after detachment of the suction-based device

a, b) Alveolar deformation and fibroblast formation were limited to the subpleural lung parenchyma, and pleural edema (or thickening) was detected in the area that had been in contact with the sucker for one hour at -540 mmHg. The alveolar deformation index was assessed to be Grade 1 in this sample. (a: Hematoxylin-eosin stain, magnification ×40; b: Elastica-Masson stain, magnification ×40)

c, d) Pleural thickening with congestion and hemorrhage were observed in the area that had been in contact with the sucker for one hour at -400 mmHg. Alveolar deformation and fibroblast formation were not detected, and the alveolar deformation index was assessed to be Grade 0 in this sample. (c: Hematoxylin-eosin stain, magnification ×40; d: Elastica-Masson stain, magnification ×40)

Video 1

The video shows that the novel device had sufficient power to stabilize and lift up the isolated lung at a suction pressure of -400 mmHg, which would enable surgeons to obtain an unobstructed view during surgery.

https://link.springer.com/article/10.1007%2Fs00464-017-5440-1

Video 2

The unmodified OVALEAD™ device tended to become detached from the lung due to the softness of the tissue and the limited insert angle during VATS. The video shows the use of the novel device to perform VATS lower lobectomy in a canine model. The device demonstrated sufficient power to stabilize the lung, and allowed a clear and unobstructed view to be obtained.

Table 1. Utility assessment of the novel lung-stabilizing device in canine video-assisted thoracoscopic surgery

Outcome measure	Conventional lung forceps (n=4)	Novel device (n=4)	*P* value[a]
Mean surgical time (minutes)	32 (25-41)	22 (14-31)	0.1096
Mean number of interruptions during surgery (range)	7.8 (6-11)	2.5 (0-7)	0.0333
Macroscopic damage of the isolated lobe	2/4	0/4	0.4286
Addition of an assist port	2/4	0/4	0.4286

[a]*P* values were calculated using the chi-square test or *t*-test as appropriate
CI, confidence intervals

Table 2. Lung damage assessment of the suction-based device and conventional lung forceps in canine models

Outcome measure	Conventional lung forceps (N=12)	Single-suction device (N=11)	Odds ratio (95% CI)	*P* value[a]
Alveolar deformation (average score)	12/12 (2.3)	5/11 (0.5)	—	0.0053
Pleural thickening	12/12	11/11	—	—
Pleural hemorrhage	4/12	2/11	2.25 0.32-15.8	0.6404
Parenchymal or alveolar hemorrhage	1/12	1/11	0.91 0.05-16.5	1.0
Stromal hypertrophy	4/12	0/11	—	—
Total score (mean)	4.25	1.73	—	0.0001

[a]*P* values were calculated using the chi-square test or *t*-test as appropriate
CI, confidence intervals

Table 3. Lung damage assessment of the suction-based device at -400 mmHg and -540 mmHg pressure in canine models

Outcome measure	-400 mmHg (N=6)	-540 mmHg (N=5)	Odds ratio (95% CI)	*P* value[a]
Alveolar deformation	2/6	3/5	3.0 (0.25-3.53)	0.5671
Pleural thickening	6/6	5/5	—	—
Pleural hemorrhage	2/6	0/5	—	0.4545
Parenchymal or alveolar hemorrhage	0/6	1/5	—	0.4545
Stromal hypertrophy	0/6	0/5	—	—
Total score (mean)	1.67	1.80	—	0.7957

[a]*P* values were calculated using the chi-square test or *t*-test as appropriate
CI, confidence intervals

Figure1

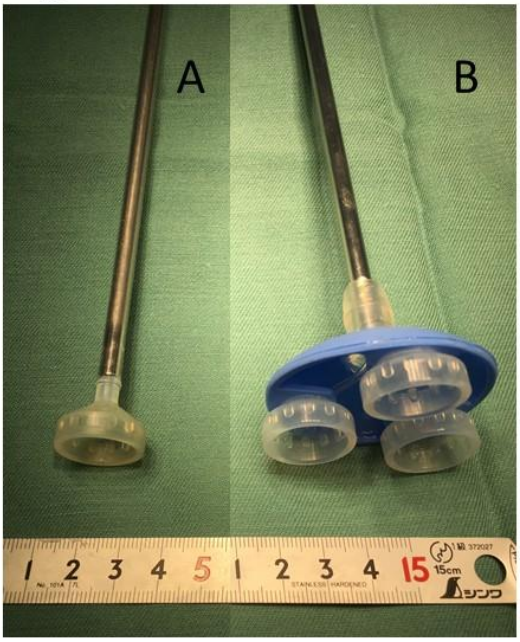
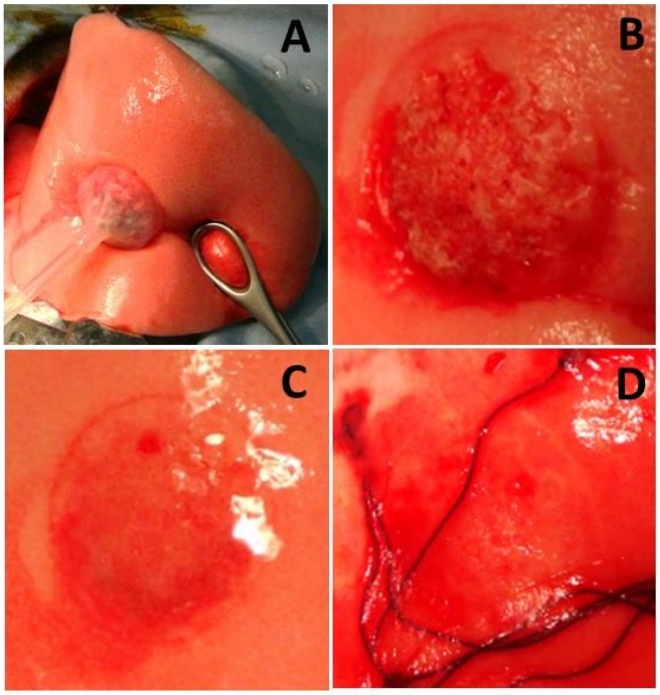


Figure2



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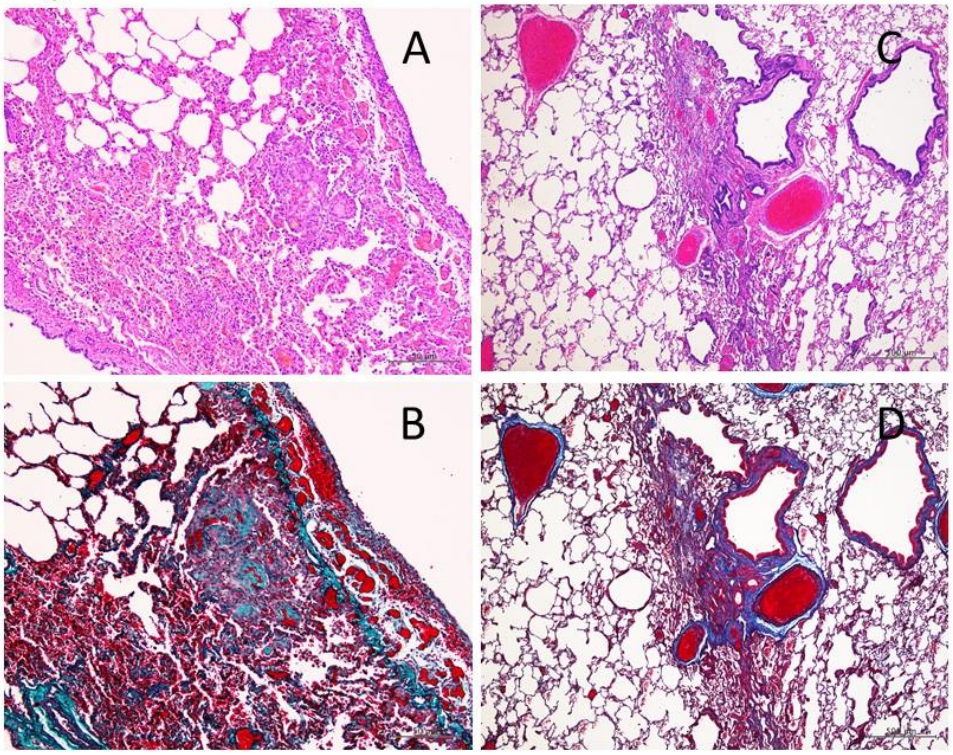
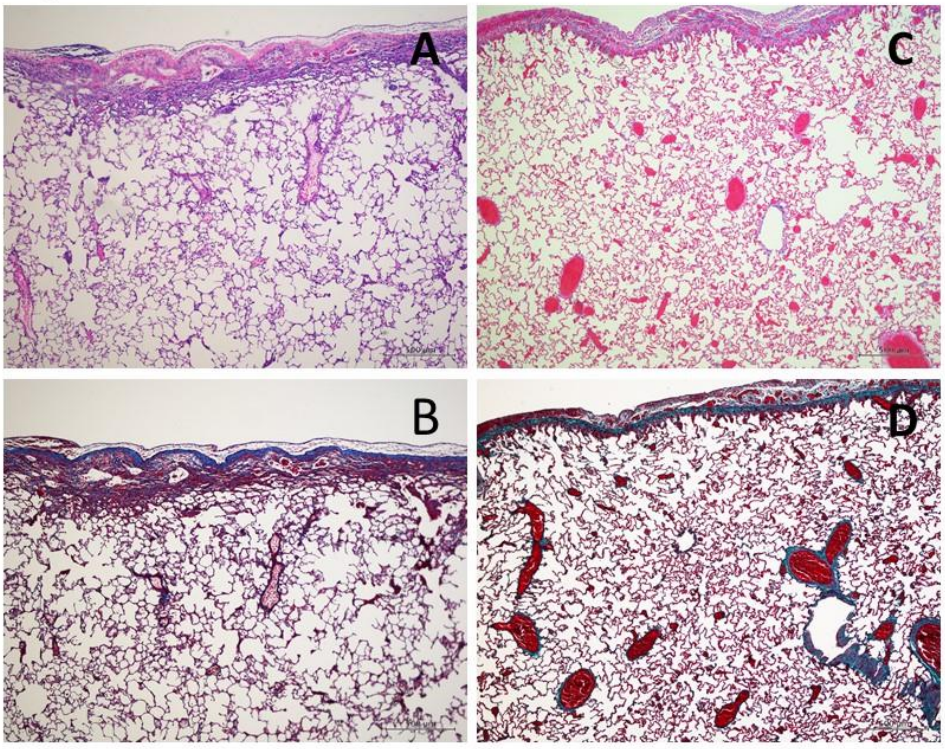


Figure4



The final publication is available at link.springer.com via

https://doi.org/10.1007/s00464-017-5440-1