Original Article

Mechanical stress in a solid ellipsoid model of the lung after thoracoscopic surgery for spontaneous pneumothorax

Byungho Lee[1], Chan Beom Park[2#], Anna Lee[1#]

[1]Department of Mechanical Engineering, Pohang University of Science and Technology, Pohang, Kyeongsangbuk-do, Republic of Korea; [2]Department of Thoracic and Cardiovascular Surgery, Incheon St. Mary's Hospital, College of Medicine, The Catholic University of Korea, Incheon, Republic of Korea

Contributions: (I) Conception and design: CB Park, A Lee; (II) Administrative support: CB Park; (III) Provision of study materials or patients: CB Park; (IV) Collection and assembly of data: B Lee; (V) Data analysis and interpretation: All authors; (VI) Manuscript writing: All authors; (VII) Final approval of manuscript: All authors.

[#]These authors contributed equally to this work.

Correspondence to: Chan Beom Park, MD, PhD. Department of Thoracic and Cardiovascular Surgery, Incheon St. Mary's Hospital, College of Medicine, The Catholic University of Korea, 56 Dongsu-ro, Bupyeong-gu, Incheon 21431, Republic of Korea. Email: drcs5223@daum.net; drcs5223@catholic.ac.kr; Anna Lee, PhD. Department of Mechanical Engineering, Pohang University of Science and Technology, 77 Cheongarm-ro, Nam-gu, Pohang, Kyeongsangbuk-do 37673, Republic of Korea. Email: annalee@postech.ac.kr.

Background: Newly formed bullae after video-assisted thoracoscopic surgery (VATS) bullectomy in primary spontaneous pneumothorax (PSP) are an important etiology for recurrence and are associated with mechanical stress along the stapling line. However, the distribution or pattern of stress after VATS bullectomy has not been thoroughly investigated. Our aim was to analyze the stress distribution following lung resection.

Methods: Using finite element method analyses in COMSOL Multiphysics software to evaluate the stress distribution along the stapling line, a solid ellipsoidal lung model was constructed. Simulations were subsequently conducted to evaluate changes in stress along the stapling line after VATS bullectomy. Finally, a parametric study investigating the changes in stress based on the difference between the lung resection volume and the degree of lung collapse was conducted.

Results: The magnitude of the stress progressively increased with the inflation of the lung, and the highest stresses were observed at both ends and the center of the stapling line. The parametric studies showed that the maximum stress observed was positively correlated with the amount of lung resection (R^2=0.961, P<0.001) and negatively correlated with the degree of lung collapse before stapling (R^2=0.964, P<0.001). A wrinkling phenomenon was also observed adjacent to the stapling line.

Conclusions: The mechanical stress during inflation progressively increased, reaching its peak at both ends and in the center, resulting in uneven wrinkling along the stapling line. Minimal resection with incomplete collapse before stapling could be considered a potential strategy to reduce stress.

Keywords: Mechanical stress; lung model; recurrence; spontaneous pneumothorax; video-assisted thoracoscopic surgery (VATS)

Submitted Oct 14, 2024. Accepted for publication Dec 20, 2024. Published online Feb 22, 2025.
doi: 10.21037/jtd-24-1728
View this article at: https://dx.doi.org/10.21037/jtd-24-1728

Introduction

Primary spontaneous pneumothorax (PSP) is a clinical manifestation that commonly occurs in young males. Video-assisted thoracoscopic surgery (VATS) bullectomy has become a standard treatment for managing PSP. VATS using staplers has several advantages, including procedural simplicity, diminished postoperative pain, cosmetic benefits, and rapid resumption of daily activity. Nevertheless, recent comprehensive studies have demonstrated a recurrent pneumothorax rate of 8.1–13.3% after VATS despite advancements in surgical techniques and stapling devices (1-6).

Young age, female sex, lower body mass index, prolonged postoperative air leakage, and incomplete resection of the diseased portion of lung tissue have been identified as risk factors for recurrence after VATS (3,7,8). Surgeons believe that resection of healthy lung tissue in the subpleural region could prevent recurrence following VATS for PSP, but extensive resection, rather than conservative resection, is associated with a higher risk of recurrence and new bullae formation (2,7). To mitigate the risk of recurrence following VATS, other surgical interventions, such as parietal pleurectomy, mechanical abrasion, and reinforcement of the staple line using synthetic materials, have been developed (9-14). Despite these advancements, the risk of recurrence remains a major concern for surgeons, primarily due to the uncertain pathogenesis of recurrence.

Highlight box

Key findings

- Stress increases at the central portion of stapling as well as both edges, leading to the occurrence of a wrinkling pattern. Parametric studies showed that minimal resection and incomplete collapse before stapling correlated with decreased stress.

What is known and what is new?

- Stress has been suggested as a significant factor in the recurrence after video-assisted thoracoscopic surgery bullectomy.
- However, due to the challenges of directly studying this phenomenon in patients, this study innovatively addressed the issue by utilizing a new lung model to replicate similar conditions and experimentally investigate the underlying mechanisms in a controlled environment.

What is the implication, and what should change now?

- The stress pattern and wrinkles can serve as clues to elucidate the pathogenesis of new bullae formation, and the results of parametric studies could form the basis for new surgical strategies to reduce stress postoperatively.

The formation of new bullae is considered to play a pivotal role in recurrent pneumothorax after VATS bullectomy. Specifically, bullae that emerge near the stapling line after VATS have shown a significant association with recurrent pneumothorax compared with newly formed bullae emerging outside the stapling line (1,15). Tsuboshima *et al.* (7) postulated that increased tension along the stapling line during reinflation results in the deformation of alveolar bronchioles near the staple line and that this deformation, in combination with the constrictive effect of a check-valve-like mechanism, plays a role in the formation of new bullae around the staple line. West (16) suggested that high apical mechanical stress and distortion of the lung are closely related to the development of bullae and the occurrence of pneumothorax. Nonetheless, there is little research on tension around the stapling line. To overcome the difficulty of directly assessing tension at the stapling site, we constructed a solid lung model to simulate stress along the stapling line after resection of bullae. Compared with previous bronchial structure modeling, porous medium modeling, and balloon modeling, our solid lung model has the advantages of simplicity and low cost.

The aim of this study was to analyze the changes in stress patterns during the reinflation process after lung resection using a stapler and to investigate variations in stress under various surgical conditions through parametric simulations of changes in lung volume and degree of collapse. This work introduces a distinct approach using the finite element method (FEM) with COMSOL Multiphysics. This simulation method using a solid lung model based on a thermomechanical analogy provides a new mechanical perspective that can enhance our understanding of PSP recurrence mechanisms and potentially inform more effective surgical strategies.

Methods

Study design and ethical approval

This study received approval from the Institutional Review Board of Incheon St. Mary's Hospital (No. OC21RISI0126 on November 5, 2021), and informed consent was waived. The study was conducted in accordance with the amended Declaration of Helsinki (as revised in 2013). The primary aim of this study was to evaluate the alterations in the stress distribution pattern along the staple line during reinflation after lung resection with a stapler. The secondary aim of this study was to investigate whether maintaining complete resection of bullous lesion is beneficial during VATS by varying the extent of lung resection. The changes in stress induced by differences in the volumes of resected lung tissue were evaluated for this purpose. Furthermore, in this study, we investigated the possibility of reducing stress at the stapling site by varying the extent of lung collapse immediately before lung resection.

Finite element model design

To evaluate the stress distribution on the stapling line, FEM analysis was performed using the COMSOL Multiphysics software module version 6.1. A model of a solid ellipsoid lung with Young's modulus of 20 kPa and a Poisson's ratio (ν) of 0.3, based on Carrie's determination of alveolar septal strain, stress, and effective Young's modulus, was constructed (17). The shape of the natural lung was asymmetric and complex, making calculations in simulations complex and time-consuming. Therefore, we adopted an ellipsoidal lung shape that closely matched the volume of an actual lung. Its geometry was defined by three semiaxes. Two dimensions along the x- and y-axes measured 50 mm each, with the third dimension, along the z-axis, measuring 120 mm. The geometric configuration was achieved utilizing axial, coronal, and sagittal chest computed tomography (CT) images of a young patient with PSP as references. The use of an ellipsoidal model reduced the computational costs owing to its geometric symmetry. An ellipsoid shape was approximated and reconstructed to match the specified dimensions (Figure S1A-S1E), and this solid lung model was assumed to have isotropic, homogeneous, and elastic properties, which did not provide an exact representation of the pressure changes within the alveoli and bronchial tree as air entered. In the natural lung, expansion occurs as air fills numerous alveoli and airways, creating internal pressure. However, replicating this intricate porous structure in a computational model is highly challenging. Instead, we used a thermal expansion coefficient of $0.02\times K^{-1}$ to simulate uniform volumetric expansion in response to temperature changes. This allowed us to achieve a simplified approximation of the overall deformation observed during lung inflation. Temperature changes, which simulate pressure changes, were based on thermomechanical analogy (18). Thermal inflation, as applied in this study, involves increasing volumetric strain through a uniform temperature change. While thermal expansion itself does not generate stress, we extracted deformation data induced by thermal expansion and used the stress-strain relationship of the material to calculate the stresses corresponding to equivalent volumetric strain. This approach enabled us to evaluate mechanical stress resulting from deformation. After applying a uniform temperature change ΔT, the stress-strain relationship is presented by using the thermal coefficient αv, and the inflation is described as $\alpha v \Delta T$. Then, $\alpha v \Delta T$ corresponds to the area change before and after inflation (Figure S2). The strain data obtained from the simulation using thermal expansion were converted into actual stress data.

VATS simulation

VATS was simulated in two main steps (Figure S3). The first step involved a stapling process in which the lung collapsed to 10% of its normal tidal volume, and a stapler was used to resect the apex of the collapsed lung. We hypothesized that the lung would collapse by 10% of its initial volume, which is comparable to the usual volume collapse observed during one-lung ventilation in young patients undergoing VATS for pneumothorax. The second step was the simulation of the reinflation of the lung. The temperature was increased while maintaining a fixed position in the stapled area to facilitate lung inflation. Inflation of the lung was terminated when the lung achieved a volume equivalent to that required for normal respiration. By excluding the complex bronchial tree, this simulation approach simplified the prediction of lung deformation without the need to model entire complex lung structures.

Parametric analysis

To comprehensively investigate the impact of changes in the resected volume and collapse ratio ($r_{collapse}$) on the stapling procedure and its associated stress distribution, a parametric analysis of the stress distribution along the stapling area was conducted using the simulation process described above. First, to change the resected volume while keeping a fixed collapse ratio of 10%, the distance from the stapling line to the apex ($d_{stapling}$) was raised from 5 to 30 mm in 1 mm intervals, with the apex of the lung serving as the reference point. Second, dstapling was fixed at 10 mm, and rcollapse, the collapsing volume divided by the original volume, was raised from 10% to 40% at 2% intervals (Figure S4).

Statistical analysis

Pearson's correlation coefficient (r) was calculated between

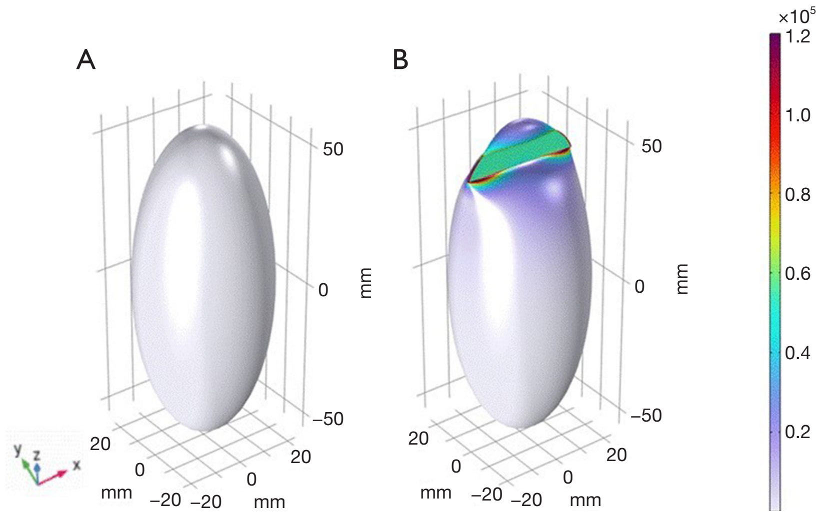

Figure 1 An immediate increase in stress occurs when the model is in its collapsed state after stapling but before reinflation with COMSOL Multiphysics. (A) Before stapling; (B) after stapling. The color scale corresponds to von Mises stress (N/m^2). $r_{collapse}$ (collapse ratio): 10%; $d_{stapling}$ (distance from the stapling line to the apex): 10 mm.

the distance from the stapling line to the apex and the measured maximal stress. It was also calculated between the ratio of collapse and the measured maximal stress. All the statistical analyses were performed using IBM SPSS Statistics for Windows (v. 26, IBM Corp.). A value of $P<0.05$ indicated statistical significance.

Results

Progressive increase in stress during inflation and wrinkling

In the first step, stapling was performed perpendicular to the z-axis while the lung collapsed to 10% of its normal volume. Stress was generated at the stapling site immediately after stapling and before inflation (*Figure 1*).

This stress increased gradually and reached its peak value when the model was maximally inflated. The stress peaked in the central region and gradually decreased towards the edges, but a sudden increase in stress was observed at the edges of the stapling area (*Figure 2*).

The stress distribution along the stapling line exhibited distinct spatial patterns (*Figure 3A*). Dual-peak patterns were observed in the outer stapling line (*Figure 3B*), one peak originating from the center of the stapling line (x=0) and the other peak arising from the terminal end of the stapling line. Along the median line, oscillations in stress were not present, revealing a curvilinear stress pattern with a single peak stress at the end of the stapling line (*Figure 3C*). The stress distribution in the outer line showed many spike-shaped peaks, which coincided with the development of wrinkles on the model surface.

Increased mechanical stress correlates with the volume of lung resection

A gradual increase in maximal stress corresponding to an increase in dstapling (from 5 to 30 mm) was observed in the series of resected sections of tissue sections, which ranged from 5 to 30 mm in dstapling. The height of the resected lung was significantly correlated with the maximal stress (R^2=0.961, P=0.001) (*Figure 4*). As the $d_{stapling}$ of the resected lung increased, an increasing trend was observed in the temperature (pressure) required to revert to the original volume (Figure S5).

Comparison of complete and incomplete lung deflation before stapling

The stress levels varied with the level of lung deflation in the parametric simulation. Incomplete deflation resulted in less stress than complete deflation. The collapse ratio was correlated with the stress level (R^2=0.964, P=0.001) (*Figure 5*). A lower temperature was required to revert to its original volume as the proportion of the collapsed lung increased (Figure S6).

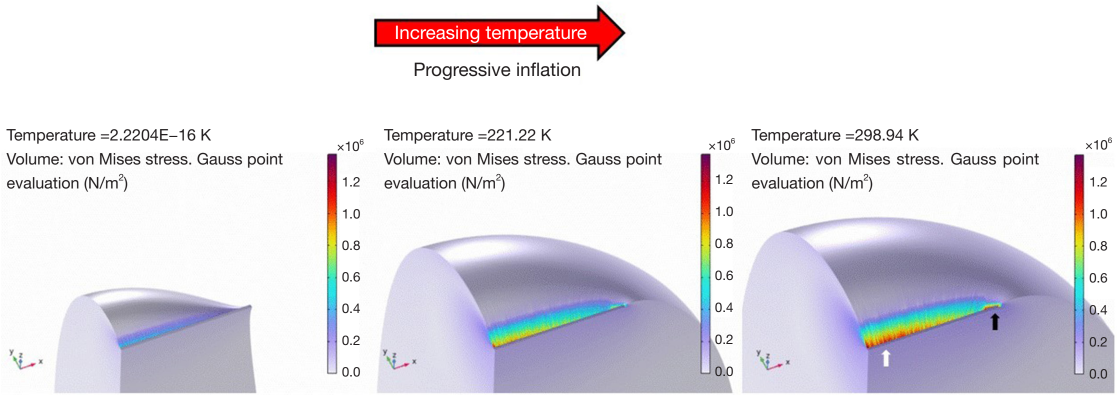

Figure 2 Continuous simulation images of lung inflation in the apex following stapling. Stress increases progressively with lung inflation. Stress was highest in the central region (white arrow), gradually decreasing toward the edges. At the edges (black arrow) of the stapling area, the stress abruptly increased.

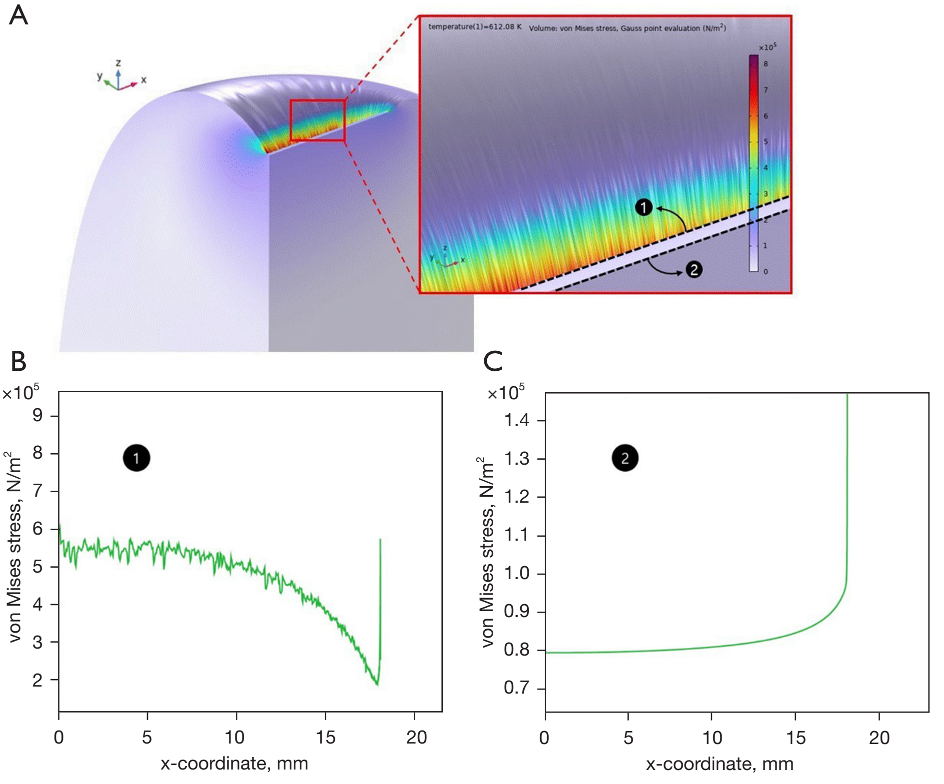

Figure 3 The stress distribution along the stapling line. (A) A distinct stress pattern can be observed in the stapling area; (B) bimodal peaks can be observed in the outer line; (C) a unimodal peak pattern can be observed in the median line, and it reaches a peak at the end of the stapling area. ①: stress along the outer stapling line; ②: stress along the median line.

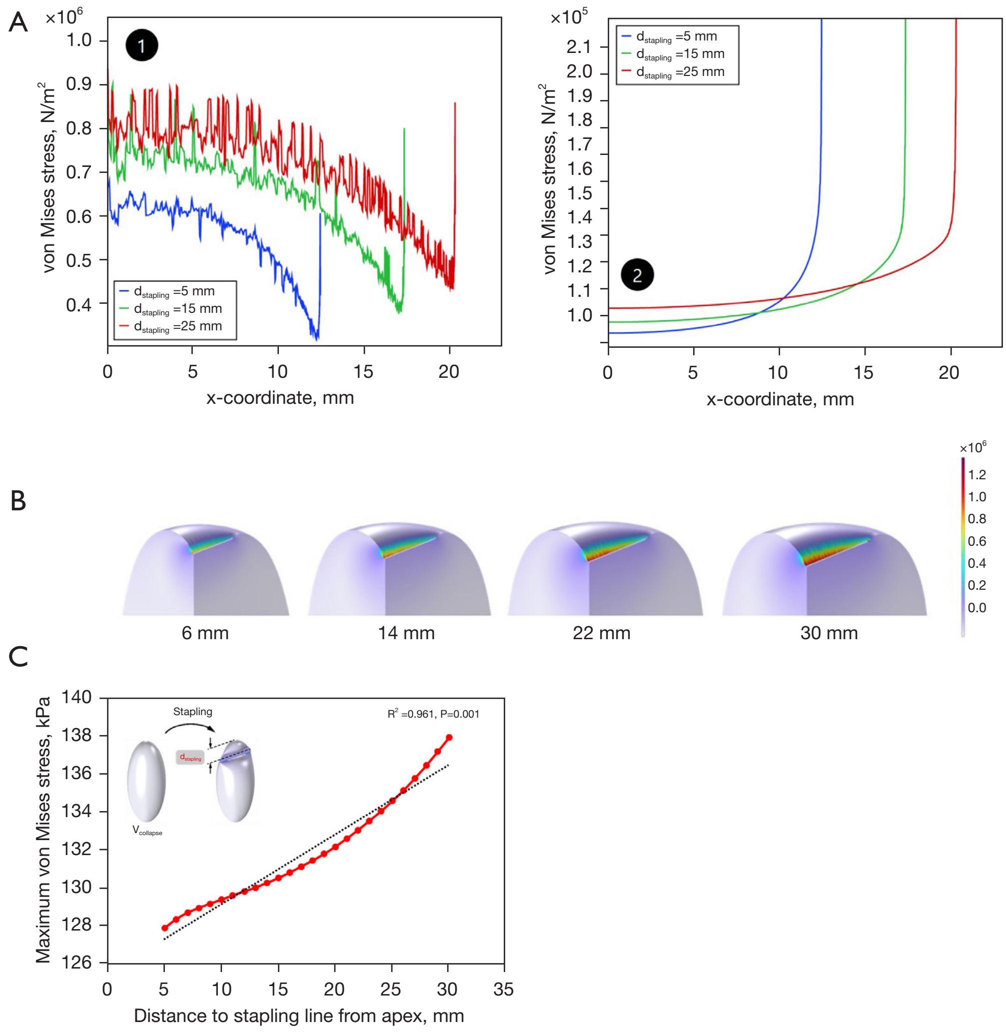

Figure 4 Parametric study according to the distance from the stapling line to the apex. (A) Stress distribution along the outer stapling line (①) and along the median line (②); (B) increased stress as dstapling changed; (C) maximum stress showed a positive correlation with the distance from the stapling line to the apex. The dotted line represents the trend line. $d_{stapling}$, distance from the stapling line.

Discussion

The findings of the present study indicate that the stress along the stapling line increases with lung inflation. The stress at the edges of the stapling line increased the most, closely followed by that in the central area of the stapling line. The volume of the resected lung and the ratio of lung collapse before stapling were correlated with the maximum stress. Additionally, a wrinkling phenomenon associated with local stress peaks was identified.

Inderbitzi *et al.* (19) postulated that incomplete resection of the diseased portion of lung tissue located adjacent to the stapling area leads to recurrence. However, several recent studies (1,2,7,8,13,15) have demonstrated that excessive resection of the lung is a significant risk factor for the postoperative formation of new bullae and that the formation of new bullae along the staple line is a strong risk factor for the recurrence of pneumothorax. Our previous study examined high-resolution CT images of patients with recurrent pneumothorax after VATS; in that study, the formation of a new bulla along the stapling line was associated with an increased risk of recurrent pneumothorax (15). These findings were consistent with those of the study by Cho *et al.* (1), which included 76 patients with ipsilateral recurrence who underwent repeated VATS; they intraoperatively observed fifty new

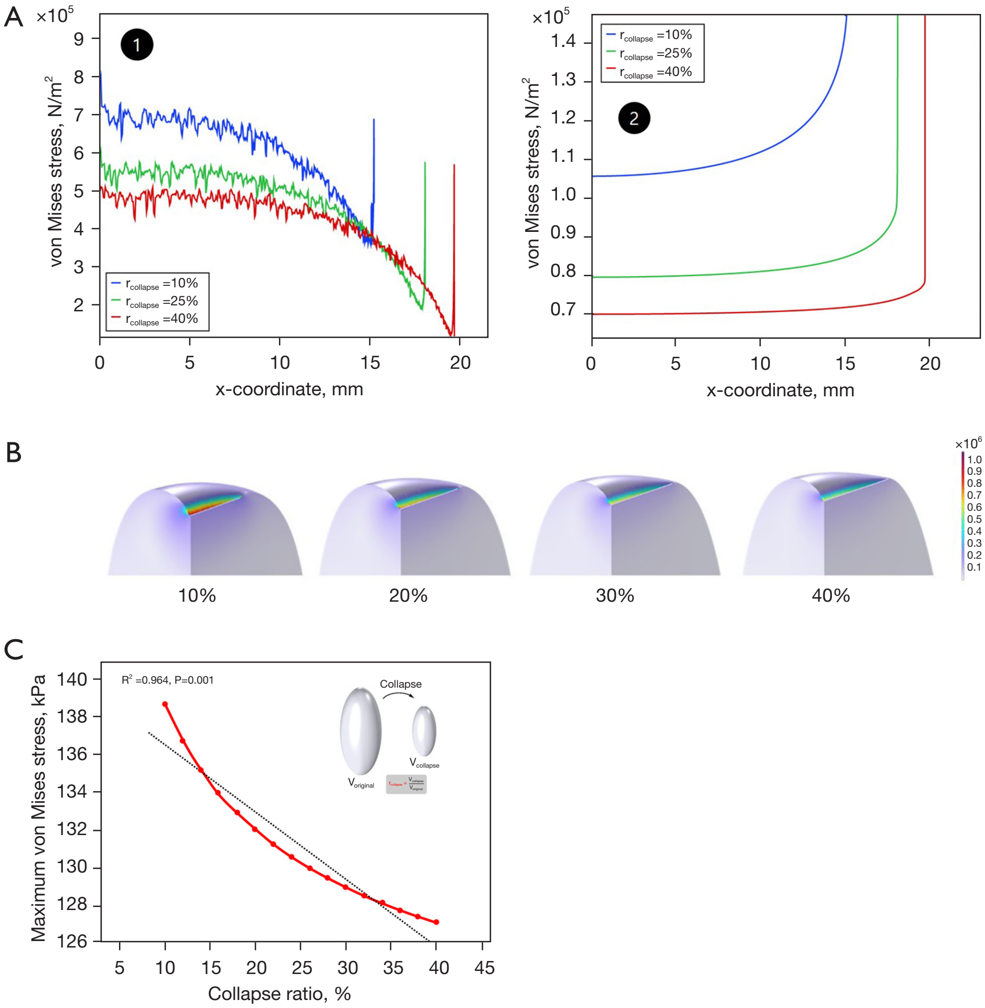

Figure 5 Parametric study according to the distance from the stapling line to the apex. (A) Stress distribution along the outer stapling line (①) and along the median line (②); (B) the stress decreased as $r_{collapse}$ increased; (C) the maximum stress showed a significant negative correlation with the collapse ratio. The dotted line represents the trend line. $r_{collapse}$, collapse ratio.

bullae on the staple line. The mechanism underlying the formation of new bullae along the stapling line is unclear, but current research suggests that tension at the staple line is the most important factor for recurrent pneumothorax following VATS (7,13,20).

West reported that mechanical failure, particularly at sites with high stress on the upper lobes, is the cause of spontaneous pneumothorax (16), but the distribution or magnitude of stress on the stapling line after VATS for PSP has not been investigated. Therefore, in this study, we constructed a solid lung model to simulate the stapling approach. We developed our solid lung structure modeling method based on the thermomechanical analogy relating temperature to pressure to avoid the high cost and complexity associated with constructing a more complex model. Our study was not focused on a functional investigation related to the intricate airways or interstitial tissue that compose the lung; instead, it is primarily an exploration of the stress exerted along the stapling line. Therefore, as described by Werner *et al.* (21), we assumed the lung model to be isotropic, homogeneous, and elastic. This thermomechanical analogy equates the solid's mechanical loading behavior to its thermal response, a method chosen despite the known differences between temperature- and pressure-induced deformations. This approach enables the estimation of lung stress distribution by inversely calculating von Mises stress from thermal expansion-induced strains. Although simplified, it offers critical insights into stress patterns around the stapling line, significantly enhancing our understanding of the mechanical stresses from surgical interventions and their potential for postoperative complications. Thus, our model effectively translates pressure variations into temperature changes for simulating lung inflation (18).

The stress that occurred immediately after stapling gradually increased until the lung was fully inflated, when it reached its maximum stress. Stapling of the lung tissue results in fixation in areas with expansile properties, preventing these areas from expanding. However, normal expansile properties are retained in the unstapled area. This discrepancy between fixation and expansibility leads to stress around the stapled area.

Here, the area with the greatest stress exhibited distinctive peak patterns. The stress gradually decreased from the center toward the edges and then increased abruptly at the edges along the outer line. The finding of high stress in the center and low stress toward the edges can be attributed to the greater thickness in the center of the stapling line. Specifically, the force required to staple thicker areas is greater than that required to staple thinner areas, contributing to the higher stress observed in the central thick region rather than toward the edges. The sudden increase in stress observed at the stapling edges is a novel finding that has yet to be explained. This finding is associated with the radial direction of the expansile force at the edges, which contrasts with the perpendicular bidirectional force experienced by the central stapling area. The expansion forces exerted in the radial direction increase the stress levels at the edges of the stapling site. Understanding these stress patterns will facilitate the development of improved stapler designs that distribute stress more evenly, which may reduce the potential for complications and improve the overall efficacy of the stapling procedure.

The presence of wrinkles adjacent to the stapling line is another novel finding of this study. Wrinkling refers to periodic or chaotic surface undulations appearing on an originally flat surface. Inhomogeneous growth or atrophy of tissues in a constrained environment induces internal residual stresses, which are believed to play a significant role in the morphogenesis of tissues (22,23). Although the residual stresses in living tissues created by growth are physiologically important for maintaining the normal biological functions of tissues (24), increased residual stresses and volumetric growth of tissue trigger morphological instabilities and induce surface wrinkling patterns. The stress occurring after stapling induces wrinkle patterns, and subsequent volumetric growth accompanying lung inflation can increase the severity of wrinkles, along with the deformation of the tissue surrounding the stapling area. The deformation of tissue accompanied by wrinkles may lead to uneven and round expansion of the lungs, thereby creating an environment favorable to the development of new bullae. However, further studies must be conducted to determine the exact role of wrinkling in the pathogenesis of new bulla formation.

The current parametric study provides direct evidence supporting the hypothesis that the volume of resected lung tissue is correlated with the stress level. The lungs have the inherent ability to return to their original volume during reinflation. A greater degree of pressure is required when the volume of the resected lung is greater, which leads to greater stress. The wrinkling amplitude tended to increase as the stress level increased, particularly in conjunction with a greater resected lung volume. Thus, a larger resection, coupled with increased stress levels and wrinkling around the stapling line, may be related to the pathogenesis of new bulla formation.

Further simulation was performed to investigate the effect of deflating the volume of the lung before stapling to alleviate the stress on the stapling line. In terms of reducing stress on the lung, incomplete lung collapse before stapling is more advantageous than complete lung collapse. However, there is a substantial risk of lung injury during the stapling procedure as the volume of the deflated lung increases. Therefore, incomplete deflation can be considered a trade-off between stress reduction and the risk of injury.

This study has several limitations. First, the pathogenesis of recurrent pneumothorax after VATS is multifactorial. While various statistical methods can adjust for risk factors, achieving exact and precise control is not possible. Simulation enables the transformation of a complex disease entity into a simplified model, enabling the investigation of a key contributing factor. While this simulation study has the limitation of not reflecting various clinical situations, it has the advantage of allowing an analysis of the presence and role of mechanical stress, which has recently been identified as the most critical risk factor for new bulla formation and recurrent pneumothorax after VATS, in isolation. Second, most previous studies depended mainly on indirect research methods utilizing resected pathology specimens (7,8,12,13). This study has the advantage of allowing the portion of the lung that remains after resection to be analyzed; this portion plays a role in the recurrence of pneumothorax. Third, this study utilizes a simplified model that focuses on isotropic volumetric expansion to derive stress distribution patterns along the stapling line. While this approach provides valuable insights, it does not explicitly account for physiological details such as pleural mechanics, suture clip thermal absorption, or parenchymal interdigitation near the suture line. Incorporating these factors in future studies could enhance the physiological relevance and accuracy of the model, enabling a more comprehensive understanding of stress distribution during lung inflation. Our parametric studies, which could not be conducted in a clinical population, provide recommendations and guidance for surgical approaches for spontaneous pneumothorax.

Conclusions

In summary, stress along the stapling line increased gradually during lung inflation and exhibited a distinctive maximal peak pattern at both the edges and in the central area of the stapling line. The extent of lung resection and the degree of lung collapse before stapling were correlated with the von Mises stress. Increased stress resulted in wrinkles along the stapling line in our simulation.

The current study could have several implications. First, in terms of surgical procedures, we recommend minimizing the volume of resected tissue whenever possible and only partially deflating the lung before stapling. Second, we propose the development of a novel material that can accommodate the inflation of lung tissue to be used for staples, along with the modification of the stapler's configuration to reduce stress at its edges. Third, stress and wrinkling during stapling might represent another recurrence mechanism, warranting further research. The implementation of these improvements in surgical procedures and devices, coupled with a deeper understanding of recurrence mechanisms, could improve the coordination between stapled and unstapled lung tissue. This, in turn, could facilitate a more effective and less stressful stapling procedure, thereby reducing the risk of recurrent pneumothorax following VATS.

Acknowledgments

This manuscript was presented at 2023 Korean Society of Thoracic and Cardiovascular Surgery 55th Annual Autumn Conference, Seoul, South Korea, November 2–4.

Footnote

Data Sharing Statement: Available at https://jtd.amegroups.com/article/view/10.21037/jtd-24-1728/dss

Peer Review File: Available at https://jtd.amegroups.com/article/view/10.21037/jtd-24-1728/prf

Funding: This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government Ministry of Science and ICT (MSIT) (No. 2022R1F1A1063438).

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://jtd.amegroups.com/article/view/10.21037/jtd-24-1728/coif). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. This study received approval from the Institutional Review Board of Incheon St. Mary's Hospital (No. OC21RISI0126 on November 5, 2021), and informed consent was waived. The study was conducted in accordance with the amended Declaration of Helsinki (as revised in 2013).

References

1. Cho S, Jheon S, Kim DK, et al. Results of repeated video-assisted thoracic surgery for recurrent pneumothorax after primary spontaneous pneumothorax. Eur J Cardiothorac Surg 2018;53:857-61.
2. Choi SY, Du Kim Y, Kim DY, et al. Influence of lung resection volume on risk of primary spontaneous pneumothorax recurrence. J Thorac Dis 2018;10:1622-7.
3. Cattoni M, Rotolo N, Mastromarino MG, et al. Analysis of

pneumothorax recurrence risk factors in 843 patients who underwent videothoracoscopy for primary spontaneous pneumothorax: results of a multicentric study. Interact Cardiovasc Thorac Surg 2020;31:78-84.
4. Liu YW, Chang PC, Chang SJ, et al. Simultaneous bilateral thoracoscopic blebs excision reduces contralateral recurrence in patients undergoing operation for ipsilateral primary spontaneous pneumothorax. J Thorac Cardiovasc Surg 2020;159:1120-1127.e3.
5. Jeong JY, Shin AY, Ha JH, et al. Natural History of Contralateral Bullae/Blebs After Ipsilateral Video-Assisted Thoracoscopic Surgery for Primary Spontaneous Pneumothorax: A Retrospective Cohort Study. Chest 2022;162:1213-22.
6. Schramel FM, Postmus PE, Vanderschueren RG. Current aspects of spontaneous pneumothorax. Eur Respir J 1997;10:1372-9.
7. Tsuboshima K, Nagata M, Wakahara T, et al. Relationship between postoperative bulla neogenesis at the staple line and the resected lung volume in primary spontaneous pneumothorax. Gen Thorac Cardiovasc Surg 2015;63:572-5.
8. Jeon HW, Kim YD, Sim SB. Should We Consider the Resected Lung Volume in Primary Spontaneous Pneumothorax? World J Surg 2020;44:2797-803.
9. Muramatsu T, Ohmori K, Shimamura M, et al. Staple line reinforcement with fleece-coated fibrin glue (TachoComb) after thoracoscopic bullectomy for the treatment of spontaneous pneumothorax. Surg Today 2007;37:745-9.
10. Lee S, Kim HR, Cho S, et al. Staple line coverage after bullectomy for primary spontaneous pneumothorax: a randomized trial. Ann Thorac Surg 2014;98:2005-11.
11. Nakanishi K. An apical symphysial technique using a wide absorbable mesh placed on the apex for primary spontaneous pneumothorax. Surg Endosc 2009;23:2515-21.
12. Sakamoto K, Takei H, Nishii T, et al. Staple line coverage with absorbable mesh after thoracoscopic bullectomy for spontaneous pneumothorax. Surg Endosc 2004;18:478-81.
13. Tsuboshima K, Nagata M, Wakahara T, et al. Association between postoperative bulla neogenesis at the staple line and resected lung weight for primary spontaneous pneumothorax: a retrospective study using the inverse-probability of treatment weighted method in patients grouped according to age. J Thorac Dis 2016;8:3676-81.
14. Ferrari PA, Santoru M, Pinna-Susnik M, et al. Additional pleural painting with iodopovidone during video-assisted thoracoscopic bullectomy for primary spontaneous pneumothorax: an observational, single-center retrospective analysis. Shanghai Chest 2022;6:20.
15. Choi SY, Kim DY, Suh JH, et al. New bullae formation in the staple line increases the risk of recurrent pneumothorax following video-assisted thoracoscopic surgery bullectomy for primary spontaneous pneumothorax. J Thorac Dis 2018;10:4287-92.
16. West JB. Distribution of mechanical stress in the lung, a possible factor in localisation of pulmonary disease. Lancet 1971;1:839-41.
17. Perlman CE, Wu Y. In situ determination of alveolar septal strain, stress and effective Young's modulus: an experimental/computational approach. Am J Physiol Lung Cell Mol Physiol 2014;307:L302-10.
18. Katsuyama Y, Yamazaki N, Kobayashi Y, et al. A study on estimation of the deformation behavior in the collapse process of lung. Annu Int Conf IEEE Eng Med Biol Soc 2012;2012:2817-22.
19. Inderbitzi RG, Leiser A, Furrer M, et al. Three years' experience in video-assisted thoracic surgery (VATS) for spontaneous pneumothorax. J Thorac Cardiovasc Surg 1994;107:1410-5.
20. Muramatsu T, Nishii T, Takeshita S, et al. Preventing recurrence of spontaneous pneumothorax after thoracoscopic surgery: a review of recent results. Surg Today 2010;40:696-9.
21. Werner R, Ehrhardt J, Schmidt R, et al. Patient-specific finite element modeling of respiratory lung motion using 4D CT image data. Med Phys 2009;36:1500-11.
22. Li B, Cao YP, Feng XQ, et al. Mechanics of morphological instabilities and surface wrinkling in soft materials: a review. Soft Matter 2012;8:5728-45.
23. Genzer J, Groenewold J. Soft matter with hard skin: From skin wrinkles to templating and material characterization. Soft Matter 2006;2:310-23.
24. Li B, Cao YP, Feng XQ. Growth and surface folding of esophageal mucosa: a biomechanical model. J Biomech 2011;44:182-8.

Cite this article as: Lee B, Park CB, Lee A. Mechanical stress in a solid ellipsoid model of the lung after thoracoscopic surgery for spontaneous pneumothorax. J Thorac Dis 2025;17(2):849-858. doi: 10.21037/jtd-24-1728

