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Automatic Quantitative Analysis of Pulmonary Vessels in CT: Methods and Applications

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Citation

Zhai, Z. (2020, March 10). *Automatic Quantitative Analysis of Pulmonary Vessels in CT: Methods and Applications*. Retrieved from <https://hdl.handle.net/1887/86281>

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Issue Date: 2020-03-10

Bibliography

- [1] R. L. R. L. Drake, W. Vogl, A. W. M. Mitchell, and H. Gray. *Gray's anatomy for students*, page 1161.
- [2] S. Standring. *Gray's Anatomy : the Anatomical Basis of Clinical Practice*. Elsevier Health Sciences UK, 2008, page 1574.
- [3] J. Tu, K. Inthavong, and G. Ahmadi. *Computational Fluid and Particle Dynamics in the Human Respiratory System*. Biological and Medical Physics, Biomedical Engineering. Dordrecht: Springer Netherlands, 2013. URL: <http://link.springer.com/10.1007/978-94-007-4488-2>.
- [4] G. Pocock and C. D. Richards. *Human physiology : the basis of medicine*. Oxford University Press, 2006, page 638.
- [5] B. M. Koeppen and B. A. Stanton. *Berne & Levy physiology*, page 829.
- [6] M. G. Levitzky. *Pulmonary physiology*. Volume 7. McGraw-Hill Medical New York, 2007.
- [7] A. T. Society. "Standards for the diagnosis and care of patients with chronic obstructive pulmonary disease (COPD) and asthma." In: *Am Rev Respir Dis* 136 (1987), pages 225–244. URL: <https://ci.nii.ac.jp/naid/10005111964/>.
- [8] G. S. Vijeyaratnam and B. Corrin. "Pulmonary alveolar proteinosis developing from desquamative interstitial pneumonia in long term toxicity studies of iprindole in the rat". In: *Virchows Archiv A Pathologische Anatomie* 358.1 (1973), pages 1–10. URL: <http://link.springer.com/10.1007/BF00555550>.
- [9] M. Hinchcliff and J. Varga. "Systemic sclerosis/scleroderma: a treatable multisystem disease". In: *Am Fam Physician* 78.8 (2008), pages 961–968.
- [10] S. Cappelli, S. B. Randone, G. Camiciottoli, et al. "Interstitial lung disease in systemic sclerosis: where do we stand?" In: *European Respiratory Review* 24.137 (2015), pages 411–419.
- [11] N. S. Goh, S. R. Desai, S. Veeraraghavan, et al. "Interstitial lung disease in systemic sclerosis: a simple staging system". In: *American journal of respiratory and critical care medicine* 177.11 (2008), pages 1248–1254.
- [12] S. Matsuoka, G. R. Washko, T. Yamashiro, et al. "Pulmonary Hypertension and Computed Tomography Measurement of Small Pulmonary Vessels in Severe Emphysema". In: *American Journal of Respiratory and Critical Care Medicine* 181.3 (Feb. 2010), pages 218–225.

- [13] D. Mukerjee, D. St. George, C. Knight, et al. "Echocardiography and pulmonary function as screening tests for pulmonary arterial hypertension in systemic sclerosis". In: *Rheumatology* 43.4 (2004), pages 461–466.
- [14] M. Delcroix, A. V. Noordegraaf, E. Fadel, et al. "Vascular and right ventricular remodelling in chronic thromboembolic pulmonary hypertension". In: *European Respiratory Journal* 41.1 (Jan. 2013), pages 224–232.
- [15] M. M. Hoeper, E. Mayer, G. Simonneau, and L. J. Rubin. "Chronic thromboembolic pulmonary hypertension". In: *Circulation* 113.16 (2006), pages 2011–2020.
- [16] Z. Zhai, H. Ota, M. Staring, et al. "Treatment Effect of Balloon Pulmonary Angioplasty in Chronic Thromboembolic Pulmonary Hypertension Quantified by Automatic Comparative Imaging in Computed Tomography Pulmonary Angiography". In: *Investigative radiology* 53.5 (2018), pages 286–292.
- [17] M. Riedel, V. Stanek, J. Widimsky, and I. Prerovsky. "Longterm follow-up of patients with pulmonary thromboembolism: late prognosis and evolution of hemodynamic and respiratory data". In: *Chest* 81.2 (1982), pages 151–158.
- [18] J. Lewczuk, P. Piszko, J. Jagas, et al. "Prognostic factors in medically treated patients with chronic pulmonary embolism". In: *Chest* 119.3 (2001), pages 818–823.
- [19] H. Takagi, H. Ota, K. Sugimura, et al. "Dual-energy CT to estimate clinical severity of chronic thromboembolic pulmonary hypertension: Comparison with invasive right heart catheterization". In: *European journal of radiology* 85.9 (2016), pages 1574–1580.
- [20] E. Mayer, D. Jenkins, J. Lindner, et al. "Surgical management and outcome of patients with chronic thromboembolic pulmonary hypertension: results from an international prospective registry". In: *The Journal of thoracic and cardiovascular surgery* 141.3 (2011), pages 702–710.
- [21] K. Sugimura, Y. Fukumoto, K. Satoh, et al. "Percutaneous Transluminal Pulmonary Angioplasty Markedly Improves Pulmonary Hemodynamics and Long-Term Prognosis in Patients With Chronic Thromboembolic Pulmonary Hypertension". In: *Circulation Journal* 76.2 (2012), pages 485–488.
- [22] M. M. Madani, W. R. Auger, V. Pretorius, et al. "Pulmonary endarterectomy: recent changes in a single institution's experience of more than 2,700 patients". In: *The Annals of thoracic surgery* 94.1 (2012), pages 97–103.
- [23] H. Mizoguchi, A. Ogawa, M. Munemasa, et al. "Refined balloon pulmonary angioplasty for inoperable patients with chronic thromboembolic pulmonary hypertension". In: *Circulation: Cardiovascular Interventions* 5.6 (2012), pages 748–755.
- [24] D. Fontein, M Klinten Grand, J. W. Nortier, et al. "Dynamic prediction in breast cancer: proving feasibility in clinical practice using the TEAM trial". In: *Annals of Oncology* 26.6 (2015), pages 1254–1262.
- [25] M. K. Ninaber, J. Stolk, J. Smit, et al. "Lung structure and function relation in systemic sclerosis: Application of lung densitometry". In: *European Journal of Radiology* 84.5 (May 2015), pages 975–979.

- [26] D. Y. Sue, A. Oren, J. E. Hansen, and K. Wasserman. “Diffusing capacity for carbon monoxide as a predictor of gas exchange during exercise”. In: *New England Journal of Medicine* 316.21 (1987), pages 1301–1306.
- [27] L. L. Pérez. “Office spirometry”. In: *Osteopathic Family Physician* 5.2 (2013), pages 65 – 69. URL: <http://www.sciencedirect.com/science/article/pii/S1877573X12001554>.
- [28] P. Callan and A. L. Clark. “Right heart catheterisation: indications and interpretation”. In: *Heart* 102.2 (2016), pages 147–157.
- [29] N. Galiè, M. Humbert, J.-L. Vachiery, et al. “2015 ESC/ERS Guidelines for the diagnosis and treatment of pulmonary hypertension”. In: *European Heart Journal* 37.1 (Jan. 2016), pages 67–119.
- [30] S. Rosenkranz and I. R. Preston. “Right heart catheterisation: best practice and pitfalls in pulmonary hypertension”. In: *European Respiratory Review* 24.138 (2015), pages 642–652.
- [31] N. H. Kim, M. Delcroix, D. P. Jenkins, et al. “Chronic thromboembolic pulmonary hypertension”. In: *Journal of the American College of Cardiology* 62.25 Supplement (2013), pages D92–D99.
- [32] I. M. Lang and M. Madani. “Update on chronic thromboembolic pulmonary hypertension”. In: *Circulation* 130.6 (2014), pages 508–518.
- [33] E. A. Kazerooni, F. J. Martinez, A. Flint, et al. “Thin-section CT obtained at 10-mm increments versus limited three-level thin-section CT for idiopathic pulmonary fibrosis: correlation with pathologic scoring.” In: *AJR. American journal of roentgenology* 169.4 (1997), pages 977–983.
- [34] M. Liu, Z. Ma, X. Guo, et al. “Computed tomographic pulmonary angiography in the assessment of severity of chronic thromboembolic pulmonary hypertension and right ventricular dysfunction”. In: *European journal of radiology* 80.3 (2011), e462–e469.
- [35] W. R. Webb, W. E. Brant, and N. M. Major. *Fundamentals of body CT*. Elsevier Health Sciences, 2014.
- [36] R. K. Kaza, J. F. Platt, R. H. Cohan, et al. “Dual-energy CT with single-and dual-source scanners: current applications in evaluating the genitourinary tract”. In: *Radiographics* 32.2 (2012), pages 353–369.
- [37] G. M. Lu, Y. Zhao, L. J. Zhang, and U. J. Schoepf. “Dual-energy CT of the lung”. In: *American Journal of Roentgenology* 199.5_supplement (2012), S40–S53.
- [38] C. A. Coursey, R. C. Nelson, D. T. Boll, et al. “Dual-energy multidetector CT: how does it work, what can it tell us, and when can we use it in abdominopelvic imaging?” In: *Radiographics* 30.4 (2010), pages 1037–1055.
- [39] M.-J. Kang, C. M. Park, C.-H. Lee, et al. “Dual-energy CT: clinical applications in various pulmonary diseases”. In: *Radiographics* 30.3 (2010), pages 685–698.

- [40] E. Hachulla, V. Gressin, L. Guillevin, et al. “Early detection of pulmonary arterial hypertension in systemic sclerosis: a French nationwide prospective multicenter study”. In: *Arthritis & Rheumatism* 52.12 (2005), pages 3792–3800.
- [41] R. D. Rudyanto, S. Kerkstra, E. M. Van Rikxoort, et al. “Comparing algorithms for automated vessel segmentation in computed tomography scans of the lung: the VESSEL12 study”. In: *Medical image analysis* 18.7 (2014), pages 1217–1232.
- [42] A. F. Frangi, W. J. Niessen, K. L. Vincken, and M. A. Viergever. “Multiscale vessel enhancement filtering”. In: *Medical Image Computing and Computer-Assisted Intervention*. Springer, 1998, pages 130–137.
- [43] Y. Sato, S. Nakajima, N. Shiraga, et al. “Three-dimensional multi-scale line filter for segmentation and visualization of curvilinear structures in medical images”. In: *Medical image analysis* 2.2 (1998), pages 143–168.
- [44] C. Xiao, M. Staring, D. Shamonin, et al. “A strain energy filter for 3D vessel enhancement with application to pulmonary CT images”. In: *Medical image analysis* 15.1 (2011), pages 112–124.
- [45] Y. Boykov and V. Kolmogorov. “An experimental comparison of min-cut/max-flow algorithms for energy minimization in vision”. In: *Energy minimization methods in computer vision and pattern recognition*. Springer, 2001, pages 359–374.
- [46] Y. Y. Boykov and M.-P. Jolly. “Interactive graph cuts for optimal boundary & region segmentation of objects in ND images”. In: *Computer Vision, 2001. ICCV 2001. Proceedings. Eighth IEEE International Conference on*. Volume 1. IEEE, 2001, pages 105–112.
- [47] Y. Boykov, O. Veksler, and R. Zabih. “Fast approximate energy minimization via graph cuts”. In: *Pattern Analysis and Machine Intelligence, IEEE Transactions on* 23.11 (2001), pages 1222–1239.
- [48] M. B. Salah, A. Mitiche, and I. B. Ayed. “Multiregion image segmentation by parametric kernel graph cuts”. In: *Image Processing, IEEE Transactions on* 20.2 (2011), pages 545–557.
- [49] B. Chen, Y. Sun, and S. H. Ong. “Liver Vessel Segmentation Using Graph Cuts with Quick Shift Initialization”. In: *The 15th International Conference on Biomedical Engineering*. Springer, 2014, pages 188–191.
- [50] C. Bauer, T. Pock, E. Sorantin, et al. “Segmentation of interwoven 3d tubular tree structures utilizing shape priors and graph cuts”. In: *Medical image analysis* 14.2 (2010), pages 172–184.
- [51] M. Freiman, N. Broide, M. Natanzon, et al. “Vessels-cut: a graph based approach to patient-specific carotid arteries modeling”. In: *Modelling the Physiological Human*. Springer, 2009, pages 1–12.
- [52] P. A. Yushkevich, J. Piven, H. C. Hazlett, et al. “User-guided 3D active contour segmentation of anatomical structures: significantly improved efficiency and reliability”. In: *Neuroimage* 31.3 (2006), pages 1116–1128.

- [53] D. Selle, B. Preim, A. Schenk, and H.-O. Peitgen. “Analysis of vasculature for liver surgical planning”. In: *Medical Imaging, IEEE Transactions on* 21.11 (2002), pages 1344–1357.
- [54] J. A. Barberà, A. Riverola, J. Roca, et al. “Pulmonary vascular abnormalities and ventilation-perfusion relationships in mild chronic obstructive pulmonary disease.” In: *American Journal of Respiratory and Critical Care Medicine* 149.2 (Feb. 1994), pages 423–429.
- [55] R. A. Pauwels, A. S. Buist, P. M. Calverley, et al. “Global Strategy for the Diagnosis, Management, and Prevention of Chronic Obstructive Pulmonary Disease”. In: *American Journal of Respiratory and Critical Care Medicine* 163.5 (Apr. 2001), pages 1256–1276.
- [56] R. Quarck, M. Wynants, A. Ronisz, et al. “Characterization of proximal pulmonary arterial cells from chronic thromboembolic pulmonary hypertension patients.” In: *Respiratory research* 13.1 (Mar. 2012), page 27.
- [57] Y. Suzuki, Y. Suzuki, T. Uto, et al. “Morphological changes in small pulmonary vessels are associated with severe acute exacerbation in chronic obstructive pulmonary disease”. In: *International Journal of Chronic Obstructive Pulmonary Disease* 11 (June 2016), pages 1435–1445.
- [58] F. Coste, G. Dournes, C. Dromer, et al. “CT evaluation of small pulmonary vessels area in patients with COPD with severe pulmonary hypertension”. In: *Thorax* 71.9 (Sept. 2016), pages 830–837.
- [59] Z. Zhai, M. Staring, M. K. Ninaber, et al. “Pulmonary Vascular Morphology Associated With Gas Exchange in Systemic Sclerosis Without Lung Fibrosis.” In: *Journal of thoracic imaging* (2019).
- [60] S. Matsuoka, G. R. Washko, M. T. Dransfield, et al. “Quantitative CT measurement of cross-sectional area of small pulmonary vessel in COPD: correlations with emphysema and airflow limitation”. In: *Academic radiology* 17.1 (Jan. 2010), pages 93–99.
- [61] K. Kubo, R.-L. Ge, T. Koizumi, et al. “Pulmonary artery remodeling modifies pulmonary hypertension during exercise in severe emphysema”. In: *Respiration Physiology* 120.1 (Mar. 2000), pages 71–79.
- [62] R. S. J. Estépar, G. L. Kinney, J. L. Black-Shinn, et al. “Computed Tomographic Measures of Pulmonary Vascular Morphology in Smokers and Their Clinical Implications”. In: *American Journal of Respiratory and Critical Care Medicine* 188.2 (July 2013), pages 231–239.
- [63] F. N. Rahaghi, J. Ross, M. Agarwal, G. González, et al. “Pulmonary Vascular Morphology as an Imaging Biomarker in Chronic Thromboembolic Pulmonary Hypertension”. In: *Pulmonary Circulation* 6.1 (Mar. 2016), pages 70–81.
- [64] R. S. J. Estépar, J. C. Ross, K. Russian, et al. “Computational vascular morphometry for the assessment of pulmonary vascular disease based on scale-space particles”. In: *2012 9th IEEE International Symposium on Biomedical Imaging (ISBI)*. IEEE, May 2012, pages 1479–1482.

- [65] F. N. Rahaghi, C. E. Come, J. C. Ross, et al. “Morphologic Response of the Pulmonary Vasculature to Endoscopic Lung Volume Reduction”. In: *Chronic Obstructive Pulmonary Diseases: Journal of the COPD Foundation* 2.3 (2015), pages 214–222.
- [66] M. Helmberger, M. Pienn, M. Urschler, et al. “Quantification of Tortuosity and Fractal Dimension of the Lung Vessels in Pulmonary Hypertension Patients”. In: *PLoS ONE* 9.1 (Jan. 2014). Edited by G. Frati, e87515.
- [67] E. M. van Rikxoort and B. van Ginneken. “Automated segmentation of pulmonary structures in thoracic computed tomography scans: a review”. In: *Physics in Medicine and Biology* 58.17 (Sept. 2013), R187–R220.
- [68] C. Xiao, M. Staring, D. Shamonin, et al. “A strain energy filter for 3D vessel enhancement with application to pulmonary CT images”. In: *Medical Image Analysis* 15.1 (Feb. 2011), pages 112–124.
- [69] R. D. Rudyanto, S. Kerkstra, E. M. Van Rikxoort, et al. “Comparing algorithms for automated vessel segmentation in computed tomography scans of the lung: the VESSEL12 study”. In: *Medical Image Analysis* 18.7 (Oct. 2014), pages 1217–1232.
- [70] A. F. Frangi, W. J. Niessen, K. L. Vincken, and M. A. Viergever. “Multiscale vessel enhancement filtering”. In: *International Conference on Medical Image Computing and Computer-Assisted Intervention*. Springer, 1998, pages 130–137.
- [71] Y. Sato, S. Nakajima, N. Shiraga, et al. “Three-dimensional multi-scale line filter for segmentation and visualization of curvilinear structures in medical images”. In: *Medical Image Analysis* 2.2 (June 1998), pages 143–168.
- [72] T. Jerman, F. Pernuš, B. Likar, and Ž. Špiclin. “Beyond Frangi: an improved multiscale vesselness filter”. In: *Medical Imaging 2015: Image Processing*. Volume 9413. International Society for Optics and Photonics. 2015, 94132A.
- [73] E. van Dongen and B. van Ginneken. “Automatic segmentation of pulmonary vasculature in thoracic CT scans with local thresholding and airway wall removal”. In: *2010 IEEE International Symposium on Biomedical Imaging: From Nano to Macro*. IEEE, 2010, pages 668–671.
- [74] Z. Zhai, M. Staring, and B. C. Stoel. “Lung vessel segmentation in CT images using graph-cuts”. In: *Medical Imaging 2016: Image Processing*. Volume 9784. International Society for Optics and Photonics. 2016, 97842K.
- [75] L. A. DeWerd and M. Kissick. *The phantoms of medical and health physics*. Springer, 2014.
- [76] V. Filippou and C. Tsoumpas. “Recent advances on the development of phantoms using 3D printing for imaging with CT, MRI, PET, SPECT, and ultrasound”. In: *Medical physics* 45.9 (2018), e740–e760.
- [77] W. G. O’dell, A. K. Gormaley, and D. A. Prida. “Validation of the Gatortail method for accurate sizing of pulmonary vessels from 3D medical images”. In: *Medical Physics* 44.12 (Dec. 2017), pages 6314–6328.

- [78] D. Mitsouras, T. C. Lee, P. Liacouras, et al. “Three-dimensional printing of MRI-visible phantoms and MR image-guided therapy simulation”. In: *Magnetic resonance in medicine* 77.2 (2017), pages 613–622.
- [79] S. Shen, H. Wang, Y. Xue, et al. “Freeform fabrication of tissue-simulating phantom for potential use of surgical planning in conjoined twins separation surgery”. In: *Scientific reports* 7.1 (2017), page 11048.
- [80] M. Toepker, G. Euller, E. Unger, et al. “Stenosis quantification of coronary arteries in coronary vessel phantoms with second-generation dual-source CT: influence of measurement parameters and limitations”. In: *American Journal of Roentgenology* 201.2 (2013), W227–W234.
- [81] M. B. Salah, A. Mitiche, and I. B. Ayed. “Multiregion Image Segmentation by Parametric Kernel Graph Cuts”. In: *IEEE Transactions on Image Processing* 20.2 (Feb. 2011), pages 545–557.
- [82] Y. Boykov, O. Veksler, and R. Zabih. “Fast approximate energy minimization via graph cuts”. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 23.11 (2001), pages 1222–1239.
- [83] Y. Boykov and V. Kolmogorov. “An experimental comparison of min-cut/max-flow algorithms for energy minimization in vision”. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 26.9 (Sept. 2004), pages 1124–1137.
- [84] B. van Ginneken, W. Baggeman, and E. M. van Rikxoort. “Robust segmentation and anatomical labeling of the airway tree from thoracic CT scans”. In: *International Conference on Medical Image Computing and Computer-Assisted Intervention*. Springer. 2008, pages 219–226.
- [85] E. Pompe, E. M. Van Rikxoort, O. M. Mets, et al. “Follow-up of CT-derived airway wall thickness: Correcting for changes in inspiration level improves reliability”. In: *European Journal of Radiology* 85.11 (Nov. 2016), pages 2008–2013.
- [86] D. Selle, B. Preim, A. Schenk, and H.-O. Peitgen. “Analysis of vasculature for liver surgical planning”. In: *IEEE Transactions on Medical Imaging* 21.11 (Nov. 2002), pages 1344–1357.
- [87] W. Dumouchel and F. O’Brien. “Integrating a robust option into a multiple regression computing environment”. In: *Computing and graphics in statistics*. Springer-Verlag New York, Inc. 1992, pages 41–48.
- [88] E. R. Weibel and D. M. Gomez. “Architecture of the Human Lung: Use of quantitative methods establishes fundamental relations between size and number of lung structures”. In: *Science* 137.3530 (Aug. 1962), pages 577–585.
- [89] E. R. Weibel. “What makes a good lung”. In: *Swiss Med Wkly* 139.27-28 (2009), pages 375–386.
- [90] R. M. S. Joemai and J. Geleijns. “Assessment of structural similarity in CT using filtered backprojection and iterative reconstruction: a phantom study with 3D printed lung vessels”. In: *The British Journal of Radiology* 90.1079 (Nov. 2017), page 20160519.

- [91] I. Hernandez-Giron, J. M. den Harder, G. J. Streekstra, et al. “Development of a 3D printed anthropomorphic lung phantom for image quality assessment in CT”. In: *Physica Medica* 57 (2019), pages 47–57.
- [92] J. Meijs, A. A. Schouffoer, N. A. Marsan, et al. “Therapeutic and diagnostic outcomes of a standardised, comprehensive care pathway for patients with systemic sclerosis”. In: *RMD Open* 2.1 (Mar. 2016), e000159.
- [93] M. R. Miller, J. Hankinson, V. Brusasco, et al. “Standardisation of spirometry”. In: *European Respiratory Journal* 26.2 (2005), pages 319–338.
- [94] B. L. Graham, V. Brusasco, F. Burgos, et al. “2017 ERS/ATS standards for single-breath carbon monoxide uptake in the lung”. In: *European Respiratory Journal* 49.1 (Jan. 2017), page 1600016.
- [95] S. Klein, M. Staring, K. Murphy, et al. “elastix: A Toolbox for Intensity-Based Medical Image Registration”. In: *IEEE Transactions on Medical Imaging* 29.1 (Jan. 2010), pages 196–205.
- [96] J. Solomon and E. Samei. “Quantum noise properties of CT images with anatomical textured backgrounds across reconstruction algorithms: FBP and SAFIRE”. In: *Medical physics* 41.9 (2014).
- [97] P. Nardelli, D. Jimenez-Carretero, D. Bermejo-Pelaez, et al. “Pulmonary Artery-Vein Classification in CT Images Using Deep Learning”. In: *IEEE Transactions on Medical Imaging* 0062.c (2018), pages 1–1.
- [98] C. Payer, M. Pienn, Z. Bálint, et al. “Automated integer programming based separation of arteries and veins from thoracic CT images”. In: *Medical Image Analysis* 34 (Dec. 2016), pages 109–122.
- [99] J.-P. Charbonnier, M. Brink, F. Ciompi, et al. “Automatic Pulmonary Artery-Vein Separation and Classification in Computed Tomography Using Tree Partitioning and Peripheral Vessel Matching”. In: *IEEE Transactions on Medical Imaging* 35.3 (Mar. 2016), pages 882–892.
- [100] N. S. Goh, R. K. Hoyles, C. P. Denton, et al. “Short-term pulmonary function trends are predictive of mortality in interstitial lung disease associated with systemic sclerosis”. In: *Arthritis & Rheumatology* 69.8 (2017), pages 1670–1678.
- [101] G. Bussone and L. Mouthon. “Interstitial lung disease in systemic sclerosis”. In: *Autoimmunity Reviews* 10.5 (2011), pages 248–255. URL: <http://www.sciencedirect.com/science/article/pii/S1568997210002089>.
- [102] E. L. Herzog, A. Mathur, A. M. Tager, et al. “interstitial lung disease associated with systemic sclerosis and idiopathic pulmonary fibrosis: how similar and distinct?” In: *Arthritis & rheumatology* 66.8 (2014), pages 1967–1978.
- [103] D. Manners, P. Wong, C. Murray, et al. “Correlation of ultra-low dose chest CT findings with physiologic measures of asbestosis”. In: *European radiology* 27.8 (2017), pages 3485–3490.

- [104] H. J. Kim, M. S. Brown, R. Elashoff, et al. “Quantitative texture-based assessment of one-year changes in fibrotic reticular patterns on HRCT in scleroderma lung disease treated with oral cyclophosphamide”. In: *European radiology* 21.12 (2011), pages 2455–2465.
- [105] J. B. West. *Respiratory physiology: the essentials*. Lippincott Williams & Wilkins, 2012.
- [106] S. G. Martin, L.-P. Kronek, D. Valeyre, et al. “High-resolution computed tomography to differentiate chronic diffuse interstitial lung diseases with predominant ground-glass pattern using logical analysis of data”. In: *European radiology* 20.6 (2010), pages 1297–1310.
- [107] J. Meijjs, A. A. Schouffoer, N. A. Marsan, et al. “A prediction model for progressive disease in systemic sclerosis”. In: *RMD open* 1.1 (2015), e000113.
- [108] B. J. Kircher, R. B. Himelman, and N. B. Schiller. “Noninvasive estimation of right atrial pressure from the inspiratory collapse of the inferior vena cava”. In: *The American journal of cardiology* 66.4 (1990), pages 493–496.
- [109] K. H. Yiu, M. K. Ninaber, L. J. Kroft, et al. “Impact of pulmonary fibrosis and elevated pulmonary pressures on right ventricular function in patients with systemic sclerosis”. In: *Rheumatology* 55.3 (2015), pages 504–512.
- [110] M. E. Bakker, M. K. Ninaber, J. Stolk, et al. “Lung Density and Pulmonary Artery Diameter are Predictors of Pulmonary Hypertension in Systemic Sclerosis”. In: *Journal of thoracic imaging* 32.6 (2017), pages 391–397.
- [111] Z. Zhai, M. Staring, and B. C. Stoel. “Lung vessel segmentation in CT images using graph-cuts”. In: *Medical Imaging 2016: Image Processing*. Volume 9784. International Society for Optics and Photonics. 2016, 97842K.
- [112] W. G. O’Dell, S. T. Govindarajan, A. Salgia, et al. “Traversing and labeling interconnected vascular tree structures from 3D medical images”. In: *Medical Imaging 2014: Image Processing*. Volume 9034. International Society for Optics and Photonics. 2014, page 90343C.
- [113] C. Terzano, V. Conti, A. Petroianni, et al. “Effect of postural variations on carbon monoxide diffusing capacity in healthy subjects and patients with chronic obstructive pulmonary disease”. In: *Respiration* 77.1 (2009), pages 51–57.
- [114] B. C. Stoel and J. Stolk. “Optimization and standardization of lung densitometry in the assessment of pulmonary emphysema”. In: *Investigative radiology* 39.11 (2004), pages 681–688.
- [115] P. H. Kitslaar, R. van’t Klooster, M. Staring, et al. “Segmentation of branching vascular structures using adaptive subdivision surface fitting”. In: *Medical Imaging 2015: Image Processing*. Volume 9413. International Society for Optics and Photonics. 2015, 94133Z.
- [116] H. J. Reesink, M. N. van der Plas, N. E. Verhey, et al. “Six-minute walk distance as parameter of functional outcome after pulmonary endarterectomy for chronic thromboembolic pulmonary hypertension”. In: *The Journal of thoracic and cardiovascular surgery* 133.2 (2007), pages 510–516.

- [117] H. J. Reesink, I. I. Tulevski, J. T. Marcus, et al. “Brain natriuretic peptide as noninvasive marker of the severity of right ventricular dysfunction in chronic thromboembolic pulmonary hypertension”. In: *The Annals of thoracic surgery* 84.2 (2007), pages 537–543.
- [118] S. Ley, J. Ley-Zaporozhan, M. B. Pitton, et al. “Diagnostic performance of state-of-the-art imaging techniques for morphological assessment of vascular abnormalities in patients with chronic thromboembolic pulmonary hypertension (CTEPH)”. In: *European radiology* 22.3 (2012), pages 607–616.
- [119] R. Krissak, T. Henzler, M. Reichert, et al. “Enhanced visualization of lung vessels for diagnosis of pulmonary embolism using dual energy CT angiography”. In: *Investigative radiology* 45.6 (2010), pages 341–346.
- [120] F. Valentin. *Hurst’s the Heart*. McGraw-Hill, 2008.
- [121] M Staring, M. Bakker, J Stolk, et al. “Towards local progression estimation of pulmonary emphysema using CT”. In: *Medical physics* 41.2 (2014).
- [122] F. Meinel, A Graef, K. Thierfelder, et al. “Automated quantification of pulmonary perfused blood volume by dual-energy CTPA in chronic thromboembolic pulmonary hypertension”. In: *RöFo-Fortschritte auf dem Gebiet der Röntgenstrahlen und der bildgebenden Verfahren*. Volume 186. 02. © Georg Thieme Verlag KG. 2014, pages 151–156.
- [123] H. Koike, E. Sueyoshi, I. Sakamoto, et al. “Quantification of lung perfusion blood volume (lung PBV) by dual-energy CT in patients with chronic thromboembolic pulmonary hypertension (CTEPH) before and after balloon pulmonary angioplasty (BPA): preliminary results”. In: *European journal of radiology* 85.9 (2016), pages 1607–1612.
- [124] T. Inohara, T. Kawakami, M. Kataoka, et al. “Lesion morphological classification by OCT to predict therapeutic efficacy after balloon pulmonary angioplasty in CTEPH”. In: *International journal of cardiology* 197 (2015), pages 23–25.
- [125] F. Rahaghi, J. Ross, M Agarwal, et al. “Pulmonary vascular morphology as an imaging biomarker in chronic thromboembolic pulmonary hypertension”. In: *Pulmonary circulation* 6.1 (2016), pages 70–81.
- [126] A. Myronenko and X. Song. “Point set registration: Coherent point drift”. In: *IEEE transactions on pattern analysis and machine intelligence* 32.12 (2010), pages 2262–2275.
- [127] S. Ge, G. Fan, and M. Ding. “Non-rigid point set registration with global-local topology preservation”. In: *Computer Vision and Pattern Recognition Workshops (CVPRW), 2014 IEEE Conference on*. IEEE. 2014, pages 245–251.
- [128] B. J. Kirby. *Micro-and nanoscale fluid mechanics: transport in microfluidic devices*. Cambridge university press, 2010.
- [129] L. K. Saul and S. T. Roweis. “An introduction to locally linear embedding”. In: *unpublished*. Available at: <http://www.cs.toronto.edu/~roweis/lle/publications.html> (2000).

- [130] A. M. Pinzón, M. H. Hoyos, J.-C. Richard, et al. “A tree-matching algorithm: Application to airways in CT images of subjects with the acute respiratory distress syndrome”. In: *Medical image analysis* 35 (2017), pages 101–115.
- [131] S. Klein, M. Staring, K. Murphy, et al. “Elastix: a toolbox for intensity-based medical image registration”. In: *IEEE transactions on medical imaging* 29.1 (2010), pages 196–205.

Publications

Journal articles

Z. Zhai, H. Ota, M. Staring, J. Stolk, K. Sugimura, K. Takase, and B. C. Stoel. Treatment effect of balloon pulmonary angioplasty in chronic thromboembolic pulmonary hypertension quantified by automatic comparative imaging in computed tomography pulmonary angiography, *Investigative Radiology*, Volume 53(5), Page 286-292, 2018 May.

Z. Zhai, M. Staring, M. K. Ninaber, J. K. de Vries-Bouwstra, A. A. Schouffoer, L. J. Kroft, J. Stolk, and B. C. Stoel. Pulmonary Vascular Morphology Associated With Gas Exchange in Systemic Sclerosis Without Lung Fibrosis, *Journal of Thoracic Imaging*, Volume 34(6), Page 373-379, 2019 November.

Z. Zhai, M. Staring , I. Hernandez-Giron , W. J. H. Veldkamp , L. J Kroft , M. K Ninaber , B. C. Stoel. Automatic quantitative analysis of pulmonary vascular morphology in CT images, *Medical Physics*, Volume 46(9), Page 3985-3997, 2019 September.

S. Bayer, **Z. Zhai**, M. Strumia, X. Tong, Y. Gao, M. Staring, B. C. Stoel, R. Fahrig, A. Nabavi, A. Maier, N. Ravikumar. Registration of vascular structures using a hybrid mixture model, *International journal of computer assisted radiology and surgery*, Volume 14(9), Page 1507-1516, 2019 September.

International conference proceedings

Z. Zhai, M. Staring and B. C. Stoel. Lung vessel segmentation in CT images using graph-cuts, *International Society for Optics and Photonics Medical Imaging*, Volume 9784, Pages 97842k, 2016 March.

Z. Zhai, M. Staring, H. Ota, and B. C. Stoel. Pulmonary vessel tree matching for quantifying changes in vascular morphology, *International Conference on Medical Image Computing and Computer-Assisted Intervention* Page 517-524, Springer Cham, 2018 September.

Z. Zhai, M. Staring, X. Zhou, Q. Xie, X. Xiao, M. E. Bakker, L. J. Kroft, B. P.F. Lelieveldt, G. J.A.M. Boon, F. A. Klok, and B. C. Stoel. Linking convolutional neural networks with graph convolutional networks: application in pulmonary artery-vein separation, *Graph Learning in Medical Imaging, MICCAI (Shenzhen) workshop*, 2019 October.

Abstracts

Z. Zhai, H. Ota, M. Staring, J. Stolk, K. Sugimura, K. Takase, and B. C. Stoel. Treatment Effect of Balloon Pulmonary Angioplasty in CTEPH, Quantified by Automatic Comparative Imaging in CTPA, *Radiological Society of North America - RSNA*, 2017.

Acknowledgements

This thesis is the result of my PhD research in the Division of Image Processing (LKEB), Department of Radiology, Leiden University Medical Center (LUMC), the Netherlands. I got a lot of support from the promotor, supervisors, cooperators, colleagues, friends, and families. I would like to express my sincere appreciations to them. I want to give my thanks to my thesis committee and opponent committee for their comments.

Firstly, I would like to give my thanks to my promotor Prof. Boudewijn Lelieveldt, and my supervisors Dr. Berend C. Stoel and Dr. Marius Staring, who provided me the position in LKEB. The LKEB is a cooperative, helpful and international lab, it is my pleasure to join the lab.

Berend, I am so lucky to have a nice supervisor like you. You are so positive and supportive to all kinds of projects. I really enjoyed the trips to conferences or visiting cooperators with you. I would like to thank you for encouraging me to the top of Zao Ski-Mountain, although I walked down with the skis on my shoulders. I also give my thanks to your wife Paulien, she is so nice driving us to the Airport deep in the night. Under your supervision, I became an independent researcher gradually. Marius, you are so helpful with all technical issues of the projects. You provided many innovative ideas and constructive comments. I would like to give my sincere acknowledgements to you.

I would also like to thank my cooperators: Jan and Maarten who gave many help in pulmonary knowledge; Eric and Duliëtte from the Department of Medicine-Thrombosis and Hemostasis; Irene, Sasha and Wouter from Medical Physics; Lucia, Anne and Jeska; Hideki and Wenyu, thank you for the support in the CTEPH project. Prof. Xuhui Zhou, Qiuxia, XiaoJuan, thank you for providing well organized data and annotations.

It is my pleasure to work with LKEB colleagues. Denis, thank you very much for all your help with MeVisLab and Pulmo. Els, I really enjoyed the concert of your 'Mandolin Orchestra ONI' and thank you so much for your help and supports for my project. Leo and Michèle, thank you for all the help in IT management. Rob, thank you for the BBQ in your house and the comfy boat trip in the summer. Jouke, you are one of the first LKEB colleagues who I knew, and thank you for the online interview and then the opportunity to join LKEB. All the members of the deep learning reading group: Hessam, Mohamed, Sahar, Kilany, Xiaowu, Qing and Qian, thank you for

sharing the cutting-edge technologies and the group discussions. Patrick, Jeroen, Niels, Alexander and Oleh, thanks for your invitation for lunch every working day. Baldur, Evgeni, Thomas, Floris, Antonios, Ahmed and Arlin, thank you very much for your nice greetings. Thanks to all desk mates of mine, Gorkem, Nora, Baas and etc, who shared the 'student island' with me.

I would also like to give my thanks to colleagues in Rotterdam, Yuanyuan, Hua, Yao, Chaoping, Bo, Gokhan, Zahra; and colleagues in Leiden, Ling, Yingguang, Yuchuan, Shengnan, Zhuo, Qing, Xiaowu, Jingnan, Xinpei, Lu, Yuanbo and Chenghong. Thanks to my friend, Xiaoyu, Xiaoyao, Zhongwu Hannah, Kun, Yang, Quanchi, Gangqi and his wife Yan; and my ex-housemates Haoyu, and his wife Tianran, Renjiang, Guiying, Wangyang and Hui.

I would like to thanks my families. 感谢我的爸爸妈妈，对我支持和理解，感谢您们的无私的爱；感谢我的岳母，大哥，大嫂以及可爱的多多，谢谢您们的支持；感谢我的姑姑，姑父，舅舅，妹妹，姐姐，哥哥，感谢您们的帮助和支持。Special thanks to my wife Ningning, you make me happy. You make me special, and you let me know what love is. Thank you for your love and selfless supports.

Curriculum Vitae

Zhiwei Zhai was born in Shandong, China in 1989. In 2008, he started his studying in the major of Information and Computing Science at Harbin Institute of Technology (Weihai) and obtained a Bachelor degree of Science in 2012. He obtained a ‘top ten outstanding students’ award (10/5000) and several ‘national scholarship’ awards. In 2012, he did a summer internship in Jinhe Company of Information and Technology (Weihai). At the same year, he began his master study in the major of Computer Science and Technology with an exemption. During the master study, he involved in the research of automatic detection and diagnosis of lung nodules based on CT images. In summer of 2013, he practiced in the Alibaba Company (Hangzhou) as an algorithm engineer. In 2014, he got his master degree of Engineering.

From September 2014, he started his PhD study in the Division of Image Processing (LKEB) under the Department of Radiology at Leiden University Medical Center in the Netherlands. His PhD project mainly focuses on pulmonary vessel analysis and quantification based on CT images, which results this thesis.

From September 2018, he works as a post-doctoral researcher in the LKEB, with the project of pulmonary artery-vein separation and quantification, based on deep learning and geometric deep learning.