



Universiteit  
Leiden  
The Netherlands

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

Zhai, Z.

### 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>

Version: Publisher's Version

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/86281>

**Note:** To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/86281> holds various files of this Leiden University dissertation.

**Author:** Zhai, Z.

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

**Issue Date:** 2020-03-10

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

Zhiwei Zhai

## **Colophon**

### **About the cover:**

The cover was designed from a tree photo taken in the Japanese Garden, Den Haag, which was made into lung-like shape. The front one is in gray, which looks like a vessel tree in medical images, and the back is in color, expressing the hope that patients suffering from diseases will recover to a colorful life.

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

ISBN: 978-94-6155-067-5

Thesis layout & cover designed by Zhiwei Zhai

Printed by Boekendeal.nl

© 2020 Zhiwei Zhai, Leiden, the Netherlands

All rights reserved. No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the copyright owner.

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

## Proefschrift

ter verkrijging van  
de graad van Doctor aan de Universiteit Leiden,  
op gezag van Rector Magnificus prof.mr. C.J.J.M. Stolker,  
volgens besluit van het College voor Promoties  
te verdedigen op dinsdag, 10 maart, 2020  
klokke 11:15 uur

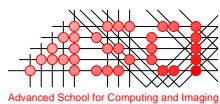
door

Zhiwei Zhai  
geboren te Taian Shandong, China in 1989

Promotor: Prof. dr. ir. B. P. F. Lelieveldt

Co-promotor: Dr. ir. B. C. Stoel  
Dr. ir. M. Staring

Leden promotiecommissie: Prof. dr. M. de Bruijne  
*Erasmus Medical Center, Rotterdam*  
Prof. dr. W. Kraaij  
Prof. dr. P.E. Postmus



The research in this thesis was performed at the Division of Image Processing (LKEB), Department of Radiology of Leiden University Medical Center, The Netherlands. This work was carried out in the ASCI graduate school. ASCI dissertation series number: 406.

Financial support for the publication of this thesis was kindly provided by:  
LKEB,  
AIR fundation,  
ASCI research school,  
Boehringer Ingelheim bv,  
Library of Leiden University,  
Lung Foundation Netherlands.

# Contents

<b>Contents</b>	<b>i</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Pulmonary anatomy and respiratory physiology . . . . .	1
1.2 Pulmonary diseases . . . . .	2
1.3 Clinical measurements for assessing SSc and CTEPH . . . . .	4
1.4 Chest CT . . . . .	6
1.5 Outline of the thesis . . . . .	6
<b>2 Lung vessel segmentation in CT images using graph-cuts</b>	<b>9</b>
2.1 Introduction . . . . .	11
2.2 Methods . . . . .	12
2.2.1 Vessel enhancement filter . . . . .	12
2.2.2 Graph representation . . . . .	12
2.2.3 Proposed cost function for the graph-cuts . . . . .	14
2.3 Experiments and results . . . . .	15
2.3.1 Parameter estimation . . . . .	15
2.3.2 Data and results . . . . .	16
2.4 Conclusion and discussion . . . . .	19
<b>3 Automatic quantitative analysis of pulmonary vascular morphology in CT images</b>	<b>23</b>
3.1 Introduction . . . . .	25
3.2 Materials and Methods . . . . .	26
3.2.1 Pulmonary vessel extraction . . . . .	26
3.2.2 Pulmonary vessel quantification . . . . .	29
3.2.3 Implementation and parameter settings . . . . .	30
3.2.4 Data sets used for validation . . . . .	31
3.3 Results . . . . .	33
3.4 Discussion . . . . .	37

3.5 Conclusions . . . . .	42
<b>4 Pulmonary vascular morphology associated with gas exchange in systemic sclerosis without lung fibrosis</b>	<b>47</b>
4.1 Introduction . . . . .	49
4.2 Materials and Methods . . . . .	49
4.2.1 Patients . . . . .	49
4.2.2 CT analysis . . . . .	50
4.2.3 Statistical analysis . . . . .	52
4.3 Results . . . . .	54
4.4 Discussion . . . . .	55
4.5 Conclusion . . . . .	59
<b>5 Treatment Effect of Balloon Pulmonary Angioplasty in CTEPH, Quantified by Automatic Comparative Imaging in CTPA</b>	<b>65</b>
5.1 Introduction . . . . .	67
5.2 Materials and Methods . . . . .	68
5.2.1 Patients . . . . .	68
5.2.2 Image analysis . . . . .	69
5.2.3 Statistical analysis . . . . .	70
5.3 Results . . . . .	73
5.4 Discussion . . . . .	74
5.5 Conclusion . . . . .	78
<b>6 Pulmonary vessel tree matching for quantifying changes in vascular morphology</b>	<b>79</b>
6.1 Introduction . . . . .	81
6.2 Methods . . . . .	82
6.2.1 Vascular tree construction . . . . .	82
6.2.2 Vascular tree matching . . . . .	82
6.2.3 Quantitative analysis . . . . .	83
6.3 Experiment . . . . .	84
6.4 Results . . . . .	85
6.5 Discussion and Conclusion . . . . .	85
<b>7 Summary and Future Work</b>	<b>91</b>
7.1 Summary . . . . .	91
7.2 Future Work . . . . .	93
7.3 General conclusions . . . . .	94

<b>Samenvatting en toekomstig werk</b>	<b>95</b>
<b>Bibliography</b>	<b>101</b>
<b>Publications</b>	<b>113</b>
<b>Acknowledgements</b>	<b>115</b>
<b>Curriculum Vitae</b>	<b>117</b>