



Universiteit  
Leiden  
The Netherlands

## Deep learning for automated analysis of cardiac imaging: applications in Cine and 4D flow MRI

Sun, X.

### Citation

Sun, X. (2023, July 5). *Deep learning for automated analysis of cardiac imaging: applications in Cine and 4D flow MRI*. Retrieved from <https://hdl.handle.net/1887/3629578>

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/1887/3629578>

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

# **Deep Learning for Automated Analysis of Cardiac Imaging: Applications in Cine and 4D Flow MRI**

**Xiaowu Sun**  
**2023**

## **Colophon**

About the cover: A word cloud and one heart appear on the cover. It denotes that in this thesis, approaches and metrics depicted in the word cloud were used to analyze the function of the heart.

Deep Learning for Automated Analysis of Cardiac Imaging: Applications in Cine and 4D Flow MRI

Xiaowu Sun

ISBN: 978-94-6483-185-6

Thesis layout: Xiaowu Sun

Cover design: Xiaowu Sun

Printed by Ridderprint BV

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: 445

Financial support for the publication of this thesis was kindly provided by:

ASCI research school,

Hart Onderzoek Nederland,

Dutch Heart Foundation,

Library of Leiden University,

Bonitus Stichting

Financial support by the Dutch Heart Foundation for the publication of this thesis is gratefully acknowledged.

© 2023 Xiaowu Sun, 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.

# **Deep Learning for Automated Analysis of Cardiac Imaging: Applications in Cine and 4D Flow MRI**

## **Proefschrift**

ter verkrijging van  
de graad van doctor aan de Universiteit Leiden,  
op gezag van rector magnificus prof.dr.ir. H. Bijl,  
volgens besluit van het college voor promoties  
te verdedigen op Woensdag 5 Juli 2023

klokke 15:00 uur

door

Xiaowu Sun  
geboren te Yantai, Shandong Province, China  
in 1992

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

Co-promotor: Dr. ir. R. J. van der Geest

Leden promotiecommissie: Prof. dr. P.H.A. Quax  
Prof. dr.ir. J.H.C. Reiber  
Prof. A.J. Nederveen  
*University of Amsterdam*  
Prof. dr. I. Isgum  
*University of Amsterdam*

# Contents

Chapter 1 General Introduction .....	1
1.1.    Cine cardiac MRI .....	1
1.2.    4D flow cardiac MRI.....	2
1.3.    Deep learning in cardiac MRI analysis.....	3
1.4.    Thesis outline .....	4
References .....	7
Chapter 2 Combination special data augmentation and sampling inspection network for cardiac magnetic resonance imaging quality classification .....	9
2.1.    Introduction .....	12
2.2.    Dataset.....	13
2.3.    Methods .....	13
2.3.1.    Data augmentation.....	13
2.3.2.    Sampling Inspection Network Architecture .....	15
2.4.    Experiments and results.....	16
2.5.    Conclusion.....	19
References .....	21
Chapter 3 SAUN: Stack attention U-Net for left ventricle segmentation from cardiac cine magnetic resonance imaging .....	23
3.1    Introduction .....	26
3.2    Methods .....	27
3.2.1    Stack model .....	28
3.2.2    Stack attention model .....	29
3.2.3    SAUN Network Architecture .....	30
3.3    Dataset and data preprocessing .....	31
3.3.1    Dataset.....	31
3.3.2    Data preprocessing and augmentation.....	32
3.4    Evaluation metrics .....	32
3.4.1.    Segmentation accuracy assessment metrics .....	33
3.4.2.    Clinical metrics.....	33
3.4.3.    Statistical analysis .....	33
3.5    Experiments and Results .....	34
3.5.1    Multi-Channel architecture.....	34
3.5.2    Results in LUD.....	35
3.5.3    Results in ACDC .....	40
3.6    Discussion .....	45
3.6.1.    Multi-Channel architecture Comparison .....	45
3.6.2.    Effect of stack attention.....	46
3.7    Conclusion.....	47

References .....	49
Chapter 4 Right Ventricle Segmentation via Registration and Multi-input Modalities in Cardiac Magnetic Resonance Imaging from Multi-disease, Multi-view and Multi-center .....	51
4.1    Introduction .....	54
4.2    Data .....	55
4.3    Method.....	55
4.3.1.    Registration.....	55
4.3.2.    Input modality of network.....	56
4.3.3.    Network Architecture .....	58
4.4    Experiments and Results .....	58
4.4.1.    Validation Set Results .....	58
4.4.2.    Testing Set Results .....	60
4.5    Conclusion.....	60
References .....	61
Chapter 5 Deep learning based automated left ventricle segmentation and flow quantification in 4D flow cardiac MRI .....	63
5.1    Background .....	66
5.2    Methods .....	67
5.2.1    Study cohort and imaging protocol .....	67
5.2.2    Ground truth generation .....	68
5.2.3    Networks.....	69
5.2.4    Evaluation metrics .....	71
5.3    Results .....	73
5.3.1    Segmentation results.....	73
5.3.2    Uncertainty results.....	79
5.3.3    Flow quantitative analysis .....	79
5.4    Discussion .....	83
5.5    Conclusions .....	85
References .....	86
Chapter 6 Transformer based feature fusion for left ventricle segmentation in 4D flow MRI .....	89
6.1    Introduction .....	92
6.2    Method.....	93
6.2.1    Attention mechanism.....	93
6.2.2    Feature Fusion Layer.....	95
6.2.3    Network Structure .....	96
6.3    Materials .....	97
6.3.1    Dataset .....	97
6.3.2    Evaluation metrics .....	98
6.4    Experiment and results .....	98

6.5 Conclusion.....	99
References .....	101
Supplementary.....	103
<b>Chapter 7 Deep Learning-based Prediction of Intra-Cardiac Blood Flow in Long-axis Cine Magnetic Resonance Imaging .....</b>	<b>107</b>
7.1 Introduction .....	110
7.2 Methods .....	111
7.2.1 Dataset .....	111
7.2.2 Data preprocessing .....	112
7.2.3 Network structure .....	113
7.3 Evaluation metrics .....	115
7.3.1 Visual evaluation .....	115
7.3.2 Quantitative evaluation metrics .....	115
7.3.3 Clinical parameters .....	116
7.3.4 Statistical analysis .....	116
7.4 Results .....	116
7.4.1 Visual comparison .....	117
7.4.2 Quantitative Results.....	118
7.4.3 E/A ratio results.....	119
7.5 Discussion .....	121
References .....	124
Supplementary.....	127
<b>Chapter 8 Summary and future work .....</b>	<b>133</b>
8.1 Summary .....	133
8.2 Discussion and Future work .....	136
8.3 General conclusions.....	137
Samenvatting en toekomstig werk.....	139
Publications .....	145
Acknowledgements .....	147
Curriculum Vitae .....	149

