# Non-invasive stroke volume assessment using the thoracic electrical bioimpedance – advances in impedance cardiography

Von der Fakultät für Elektrotechnik und Informationstechnik der Rheinisch-Westfälischen Technischen Hochschule Aachen zur Erlangung des akademischen Grades eines Doktors der Ingenieurswissenschaften genehmigte Dissertation

vorgelegt von

Dipl.-Ing. Mark Ulbrich
aus Bonn

Berichter: Univ.-Prof. Dr.-Ing. Dr. med. Steffen Leonhardt
Univ.-Prof. Dr. Tech. Jaakko Antero Malmivuo

Datum der mündlichen Prüfung: 29.01.2016

Aachener Beiträge zur Medizintechnik 39
Herausgeber:
Univ.-Prof. Dr.-Ing. Dr. med. Steffen Leonhardt
Univ.-Prof. Dr.-Ing. Klaus Radermacher
Univ.-Prof. Dr. med. Dipl.-Ing. Thomas Schmitz-Rode

**Mark Ulbrich**

# Non-invasive stroke volume assessment using the thoracic electrical bioimpedance

- advances in impedance cardiography

Ein Beitrag aus dem Philips Lehrstuhl für Medizinische Informationstechnik (MedIT) am Helmholtz-Institut für Biomedizinische Technik der RWTH Aachen
(Direktor: Univ.-Prof. Dr.-Ing. Dr. med. Steffen Leonhardt).

RWTH AACHEN UNIVERSITY

Shaker Verlag
Aachen 2016

**Bibliographic information published by the Deutsche Nationalbibliothek**
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: D 82 (Diss. RWTH Aachen University, 2016)



Printed in Germany.

ISBN 978-3-8440-4411-9
ISSN 1866-5349

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen
Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9
Internet: www.shaker.de • e-mail: info@shaker.de

# Acknowledgment

In general, I would like to thank all persons who directly or indirectly participated in this thesis. The order in which people are listed below is chosen arbitrarily.

A special thanks goes to Prof. Dr.-Ing. Dr. med. Steffen Leonhardt. As head of the Philips Chair for Medical Information Technology (MedIT), he gave me the unique opportunity to do research in medical technology with a high degree of freedom to realize my ideas. Thus, I could develop my own individuality and self-sufficiency independently in combination with challenging and interesting projects and a substantial portion of fun. I also thank all others at the chair for fruitful and constructive discussions, especially Marian Walter, Walter Wrobel, Daniel Teichmann and Anton Tholen. I would also like to thank Prof. Dr. Tech. Jaakko Malmivuo to assume the co-referee for this thesis.

I would like to gratefully and sincerely thank Jens Mühlsteff for his guidance, teamwork and his valuable remarks and advice he gave me related to most of the topics of my thesis. As an expert in his field, he could give me his own point of view on all important topics leading to an improved, more efficient and focused way to solve problems occurring during the research for this thesis.

I thank Lisa Röthlingshöfer and Axel Cordes who literally forced me to apply for a job at MedIT. They fortunately convinced me.

I would like to thank all project partners for everything we achieved together, especially Auli Sipilä and Merja Kamppi from Clothing+ for the pleasant and constructive cooperation. I also thank Michael Czaplik, Matthias Zink, Thorsten Janisch and Fabienne Wolf from the University Hospital Aachen.

I thank all proofreaders of this thesis: Jens Mühlsteff and Sören Weyer (the ones who read everything), Katrin Lunze, Urs Enke and Boudevijn Venema.

Many thanks go also to my students whose excellent work contributed to this thesis: Piotr Paluchowski, Alexander Schauermann, Tingting Wan and Niklas Koep; not to forget all my student workers who supported me during my time as an employee at the chair.

Finally, and maybe most importantly, I would like to thank those whose psychical support let me come this far. This comprises family and friends, and those are in detail:

Bettina Amann for her constant telemotivations; Dagmar Förster who helped me altruistically during my studies when I faced hard times; Thomas Herold because he probably is the most competent man to satisfy one's thirst as well as Andrej Stender and Olivier Graf who were always receptive for personal and professional problems.

One institution that also made work at the chair really pleasant is the *Competence at Glass Community of Interest* (Interessengemeinschaft Kompetenz am Glas), and I thank all co-founders, especially Boudevijn Venema, and members for the joyful time we spent together.

I also thank my family, especially my grandmother and my mother, for supporting me throughout my studies and my PhD time.

# Abstract

Monitoring the human stroke volume or cardiac output non-invasively is a challenging task which has kept scientists and researchers occupied for decades. Impedance cardiography provides the possibility to estimate the stroke volume using a harmless alternating current (AC) injected into the body. This thesis presents new research in this field.

A new application area in medical care is introduced in the form of a wearable impedance cardiograph integrated into a shirt for home monitoring in a personal healthcare scenario. Therefore, conductive textile materials were analyzed and used as electrodes and electrical wiring in a suitable garment. The garment provides an easy connection to the lightweight hardware which transmits the data wirelessly to a receiving station. Thus, monitoring patients 24/7 is possible.

In addition, physiological sources contributing to the impedance waveform were analyzed using a 4D model of the human thorax and finite element simulations. The results show that blood conductivity changes due to red blood cell orientation are the major contributor to the impedance signal. The second factor influencing the impedance is aortic wave propagation, whereas lung conductivity and heart volume changes compensate each other.

With this model, negative influences of heart failure on the measured impedance were identified. These results were verified by results obtained from clinical trials: a recompensation study and a pleural drainage study. It could be shown that with increasing lung conductivity due to lung edema or pleural effusion, the impedance decreases, leading to a lower stroke volume.

Furthermore, improved algorithms to assess characteristic points in the impedance cardiogram were introduced, performing better than those in a commercially available reference device. Therefore, the discrete wavelet transform was used to get better estimates for the opening and the closure of the aortic valve as assessed by Doppler echocardiography.

Last but not least, completely new application areas outside classical medical care scenarios were made accessible by human trials. In one trial, the feasibility of impedance cardiography to estimate the blood alcohol content was analyzed, showing promising results. In another trial, the stroke volume of sport divers was assessed to characterize different stages of underwater apnea. It could be shown that the stroke volume decreases in the easy-going apnea phase and increases in the subsequent struggle phase dominated by diaphragm contractions.

# Contents