

Cardiovascular autonomic dysfunction impact on cardiovascular complications across glucose metabolism

PhD dissertation

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Cover Page

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Notes and disclosures

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Preface

The research presented in this dissertation was conducted during my PhD studies at the Department of Public Health, Aarhus University, and Steno Diabetes Center Aarhus, between 2022 and 2025. The project was supported by the Department of Public Health at Aarhus University, Steno Diabetes Center Aarhus, and the European Foundation for the Study of Diabetes/Sanofi European Diabetes Research Programme in Diabetes associated with Cardiovascular Disease. The aim was to better understand the impact of cardiovascular autonomic dysfunction on heart disease in individuals with diabetes or high risk of diabetes. I am grateful for the opportunity to explore how autonomic dysfunction can be demonstrated by investigating variations in heart rate responses across different durations and conditions to gain insights into cardiovascular risk, which remains ongoing issue in current research. It is my hope that the findings of this dissertation will contribute to a deeper understanding of the clinical potential of long-term heart rate variability measures and standardized cardiovascular autonomic reflex tests in identifying individuals at risk for cardiovascular disease across all stages of glucose metabolism. In doing so, I hope this work contributes to the broader effort of improving care for individuals at risk of developing diabetes, as well as those living with the diabetes.

Other work and collaboration during the PhD

Much of the work I have been involved in during my PhD is not fully reflected in this dissertation. I would like to take this opportunity to provide an overview and acknowledge the many collaborative establishment that sprouted during my time as a PhD student.

In my work on diabetes epidemiology, I have been deeply curious about the future methods in research. This led me to become a peripheral member of the Hulman Lab, a group with an open heart and a strong foundation in critical thinking, focused on machine learning and clinical prediction. Together with Adam Hulman and Anders Isaksen, we investigated how people perceive the use of artificial intelligence in healthcare. On this project, I am grateful to Lasse Bjerg and Annelli Sandbæk and rest of Health in Central Denmark (HICD) steering committee for integrating our questionnaire into their cohort. I also appreciate Kasper Normann's help with prompt data management. This collaboration resulted in one original research paper and two other submitted manuscript based on wave 2022 and 2024 of data collection from the HICD cohort.

We set out to extend the generalisability of the CANCAN findings to populations without type 2 diabetes. This led us to use data from the Lolland-Falster Health Study (LOFUS). I am deeply grateful to Randi Jepsen for the collaboration on accessing the cohort and for her support in getting the biobank samples analysed. The data is now ready for use in the study. Further appreciation goes to Marie Mathilde Bjerg Christensen, Christian Stevns Hansen, and Jesper Fleischer for updating reference values for CARTs using LOFUS data and for generously sharing their expertise on the measurements.

In my last year of the PhD is was lucky to exchange research environment to Baker Heart and Diabetes Institute. I had the privilege of working alongside a proficient team of epidemiologists consisting of PhD students, postdoctoral researchers, and senior scientists, using data from the PREDICT study involving patients with type 2 diabetes. I was impressed by how closely research and clinical care are integrated. Furthermore, their dedication to utilizing cohorts and organizing multinational data resources was admirable. I would like to extend a special thank to Professor Dianna Magliano, Senior Researcher Julian Sacre, and Professor Jonathan Shaw for their valuable input on using

questionnaires to screen for heart failure subtypes and for helping to shape a study that will be submitted soon.

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This PhD journey has been a remarkable adventure. The best part has undoubtedly been all the people I have met and worked with along the way. I would like to express my deepest gratitude to colleagues, collaborators, friends, and family for their support throughout this journey and for making the ride both fun and exciting.

First and foremost, I would like to thank my main supervisor, Daniel Witte. His unwavering support, thought-provoking challenges, and brilliant guidance have kept me motivated to learn about diabetes epidemiology throughout this journey. His ability to expand horizons in research has been truly inspiring, and I am deeply grateful for the opportunities to grow under his mentorship. I would like thank the rest of the supervisor team. Lasse Bjerg for his methodological support, high spirits and sharp minded, always cutting straight to the core of the research. Signe T. Andersen for her guidance and support throughout the design and data collection of the CANCAN study. As a non-clinician researcher, it was eye-opening to witness the complex challenges of diabetes consultations, and I admire her ability to understand each patient. Christian Stevns Hansen for his prompt support and strong physiological expertise.

Thank you to all my friends at Steno Diabetes Center Aarhus (SDCA) and the Department of Public Health at Aarhus University who have supported my project, inspired great discussions, and shared fun times: Adam, Omar, Luke, Daniel I, Anders, Benjamin, Jie, Livie, Helene, Sidsel, Manuel, Christian, and Ole-Emil.

In The Maastricht Study, I would like to thank Marleen van Greevenbroek, Miranda Schram, Carla van der Kallen, and the rest of the team for granting me access to the cohort and for showing me the data collection facilities. Thanks to Marion Feijge for guiding me through the data. I am also grateful to Professor Coen Stehouwer for his sharp insight and deep expertise in diabetes epidemiology. In the ADDITION-PRO study, I would like to thank Anne-Louise Bjerre and Søren Brage for their help in explaining variables, and data manager Marianne at the Department of Public Health for her generous support. In the CANCAN study, I would like to acknowledge Henrik Holm Thomsen and Gitte Jensen for their help with recruitment, and Anne Katrine Møller Gramstrup for extracting clinical data for the study population. I am also deeply grateful to the people who generously agreed to participate in the CANCAN study.

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No adventure is truly exciting without cultural exchange—whether through the lovely visits from Peter and Ieva at SDCA or by immersing myself in new research environments. To Professor Dianna Magliano and Professor Jonathan Shaw, thank you for including me in the Epidemiology group at the Baker Heart and Diabetes Institute in Melbourne. It was a truly enriching stay, both scientifically and socially. I would like to extend my sincere thanks to Julian Sacre for his valuable support and insightful contributions in deepening my understanding of the challenges involved in diagnosing heart failure subtypes. To the PhD students and post-docs at 7/11, Della, Forough, Elizabeth, Jedidiah, Lei, Mahtab, Kanika and Joanna, thank you for making me feel so welcomed and giving me a wonderful and fun experience of Melbourne.

To my brothers Esben and Jalte, thank you for putting up with me and for helping me loosen up and have fun. To my parents, thank you for supporting me throughout my life and for standing by me in every path I have chosen. Much of my curiosity for applying mathematics and statistics to understand the world stems from my grandfather, Ebbe Schaarup, who spent countless hours teaching and inspiring me. A large part of this work is dedicated to him. Last but not least, to my lovely girlfriend Freja, thank you for always being kind, supportive, and willing to join the adventure.

Papers in the dissertation

Study I

Cardiovascular autonomic dysfunction is linked with arterial stiffness across glucose metabolism: The Maastricht Study

Jonas R. Schaarup, Lasse Bjerg, Christian S. Hansen, Signe T. Andersen, Marleen van Greevenbroek, Miranda T. Schram, Bastiaan E. de Galan, Coen Stehouwer, Daniel R. Witte (2025). medRxiv 2024.12.03.24317865; doi: <https://doi.org/10.1101/2024.12.03.24317865> (preprint) (under peer-review at BMJ Open Diabetes Research & Care)

Study II

Cardiovascular autonomic dysfunction precedes cardiovascular disease and all-cause mortality: 11-year follow-up of the ADDITION-PRO study

Jonas R. Schaarup, Lasse Bjerg, Christian S. Hansen, Erik L. Grove, Signe T. Andersen, Dorte Vistisen, Søren Brage, Annelli Sandbæk, Daniel R. Witte (2025). medRxiv 2024.12.18.24319131; doi: <https://doi.org/10.1101/2024.12.18.24319131> (accepted at Diabetes, Obesity and Metabolism)

Study III

Cardiovascular autonomic neuropathy and indices of heart failure in type 2 diabetes: The CANCAN Study

Jonas R. Schaarup, Lasse Bjerg, Christian S. Hansen, Daniel R. Witte, Henrik H. Thomsen, Jesper Fleischer, Rodica Pop-Busui, Annelli Sandbæk, Signe T. Andersen. (submitted?)

Additional publications

The 2 following original research studies and 2 preprints have been published during the PhD period, but have not been included in the dissertation.

Peer-reviewed

Schaarup JR, Christensen MS, Hulman A, Hansen CS, Vistisen D, Tabák AG, Witte DR, Bjerg L. Autonomic dysfunction is associated with the development of arterial stiffness: The Whitehall II cohort. *GeroScience*, 2023. <https://doi.org/10.1007/s11357-023-00762-0>

Schaarup JR, Aggarwal R, Dalsgaard E-M, Norman K, Dollerup OL, Ashrafi H, Witte DR, Sandbæk A, Hulman A. Perception of artificial intelligence-based solutions in healthcare among people with and without diabetes: A cross-sectional survey from the health in Central Denmark cohort. *Diabetes Epidemiology and Management*, 2023. <https://doi.org/10.1016/j.deman.2022.100114>

Pre-prints

Jonas R. Schaarup, Anders Aasted Isaksen, Kasper Norman, Lasse Bjerg, Adam Hulman. (2025). Trust in large language model-based solutions in healthcare among people with and without diabetes: a cross-sectional survey from the Health in Central Denmark cohort. medRxiv 2025.02.24.25322734; doi: <https://doi.org/10.1101/2025.02.24.25322734> (under review at BMJ digital health and AI)

Anders Aasted Isaksen, **Jonas R. Schaarup**, Lasse Bjerg, Adam Hulman. (2025). Changes in public perception of AI in healthcare after exposure to ChatGPT. medRxiv 2025.01.23.25321048; doi: <https://doi.org/10.1101/2025.01.23.25321048> (under review at npj digital medicine)

Table of contents

List of Figures

List of Tables

Abbreviations

- BMI:** Body mass index
CAN: Cardiovascular autonomic neuropathy
CARTs: Cardiovascular autonomic reflex tests
CD: Carotid artery distensibility coefficient
cf-PWV: Carotid-femoral pulse wave velocity
CI: Confidence interval
CVD: Cardiovascular disease
eGFR: Estimated glomerular filtration rate
FPG: Fasting plasma glucose
GLP1RA: Glucagon-like peptide-1 receptor agonists
HDL: High-density lipoprotein cholesterol
HRV: Heart rate variability
IR: Incidence rate
IRR: Incidence rate ratio
HbA1c: Haemoglobin-A1c
LDL-C: Low-density lipoprotein cholesterol
MACE: Three-point major adverse cardiovascular events
NGM: Normal glucose metabolism
NT-proBNP: N-terminal pro-B-type natriuretic peptide **OGTT:** Oral glucose tolerance test
OR: Odds ratio
PAEE: Physical activity energy expenditure
RPAQ: Recent Physical Activity Questionnaire
SBP: Systolic blood pressure
DBP: Diastolic blood pressure
SGLT2i: Sodium glucose co-transporter type 2 inhibitors
SES: Socioeconomic status
SD: Standard deviation
SDNN: Standard deviation of NN intervals
SDANN: Standard deviation of the averages of NN intervals in 5-minute segments
SDNN index: Mean of the SDs of all NN intervals for all 5-minute segments
pNN50: Proportion of NN intervals differing by more than 50 ms
RMSD: Root mean square of successive differences between NN intervals

Abbreviations

TP: Total power (variance of NN intervals 0.4 Hz)

ULF: Ultra low-frequency range (0.003 Hz)

VLF: Very-low-frequency range (0.003–0.04 Hz)

LF: Low-frequency range (0.04–0.15 Hz)

HF: High-frequency range (0.15–0.4 Hz)

T2D: Type 2 diabetes mellitus

TC: Total cholesterol

TG: Triglycerides

UACR: Urine albumin-to-creatinine ratio

1 Introduction

Diabetes mellitus is a growing global health concern, posing pressing challenges for public health systems.¹ As prevalence rises, more individuals are exposed to an increased risk of premature mortality and cardiovascular disease (CVD).¹ At the same time, people live longer with diabetes, and therefore endure extended periods under the burden of diabetes-related complications.² Despite advancements in cardiovascular care, coronary artery disease and heart failure are still often detected at more advanced stages, such as during ischemia, major cardiovascular events, or the onset of symptomatic heart failure in patients with diabetes.^{[3]4}

Over the last decades, cardiovascular autonomic dysfunction has repeatedly gained attention as a risk factor for CVD.⁵ Heart rate variability (HRV) is considered a reliable marker for measuring autonomic function, as it reflects the balance between sympathetic and parasympathetic modulation of heart rate intervals.⁶ Despite its recognition as a CVD risk factor, assessment of cardiovascular autonomic dysfunction has not been implemented in healthcare practice. In diabetes, lower HRV is regarded as an early indicator of cardiovascular autonomic neuropathy (CAN), which is diagnosed using cardiovascular autonomic reflex tests (CARTs).⁷ Signs of autonomic dysfunction, may already be present in individuals with prediabetes.⁸ Despite rising prevalence and increased CVD risk, people with prediabetes often remain outside structured treatment pathways .^{[9]10} Although diabetes contributes to autonomic dysfunction, it is still unclear at what stage in the diabetes risk spectrum HRV and CARTs become clinically useful for assessing CVD risk.

In the past, measuring HRV needed special instruments like an electrocardiogram. Today, it's easy to track HRV with everyday devices like smartwatches.^{[11]12} This increased accessibility allows for continuous monitoring and a better understanding of HRV over extended periods and under various free-living conditions.¹³ However, long-term HRV patterns and the relation between specific diurnal responses and risk of cardiovascular complications remain less well understood.

The overall aim of this dissertation is to understand how cardiovascular autonomic dysfunction/CAN affects cardiovascular disease risk (i.e. heart failure, stroke, myocardial infarction) and specific subclinical markers of CVD: carotid-femoral pulse wave velocity and carotid artery distensibility in populations covering the whole glycemic continuum, from healthy glucose metabolism to type 2 diabetes.

2 Background

This background introduces the concept of type 2 diabetes (T2D) and its associated cardiovascular risk. It then provides an overview of various cardiovascular complications, including arteriosclerosis, atherosclerosis, and heart failure. Finally, it describes cardiovascular autonomic function (autonomic function) and its potential to enhance our understanding of CVD.

2.1 Type 2 diabetes and prediabetes

The progression from normal glucose metabolism to T2D is characterized by sustained elevations in blood glucose levels. T2D is characterized by a progressive decline in beta-cell function, most often as a consequence of chronic insulin resistance.^{14,15} Insulin resistance occurs when certain tissues, such as muscle and liver tissues, lose their sensitivity to insulin.¹⁵ As a result, glucose is not effectively taken up by these tissues and remains in the circulation.¹⁵ Meanwhile, beta-cell function deteriorates, leading to a diminished insulin response to glucose levels.¹⁵ Years before a T2D diagnosis, these changes contribute to rising fasting and postprandial glucose levels.¹⁴

The body regulates glucose through various mechanisms. During fasting, pancreatic alpha cells secrete glucagon, which stimulates hepatic glucose production via glycogenolysis and gluconeogenesis.¹⁵ After a meal, rising blood glucose levels stimulate pancreatic beta cells to release insulin and trigger the secretion of incretins, such as glucagon-like peptide-1 (GLP-1) from the intestines.¹⁵ Insulin and incretins work together to suppress hepatic glucose production, while insulin promotes glucose uptake in muscle and adipose tissue.¹⁵ Excess glucose is primarily stored as glycogen in the liver and muscles, with some converted to triglycerides for long-term storage. Multiple organs, including the pancreas, liver, kidneys, intestines, muscle, and adipose tissue are involved in this coordinated process.¹⁵ The autonomic nervous system plays a supportive role in glucose homeostasis by modulating metabolic activity. Parasympathetic signals tend to reduce glucose production, while sympathetic signals enhance it, especially during hypoglycemia.¹⁵

The World Health Organization (WHO) and American Diabetes Association (ADA) diagnostic criteria for T2D include fasting plasma glucose 7.0 mmol/L, 2-hour plasma glucose 11.1 mmol/L during an oral glucose tolerance test (OGTT), or hemoglobin A1c (HbA1c) 6.5% (48 mmol/mol).^[16]^[17] The OGTT measures glucose levels two hours after the ingestion of a standard 75-gram glucose load in the fasting state^[17]. Progression towards diabetes is a continuous process, with type 2 diabetes defined based on glucose thresholds associated with an increased risk of diabetes-specific microvascular complications, particularly retinopathy^[18]. Many complications of diabetes, such as macrovascular disease, neuropathy, cancer, and cognitive impairment, may start to develop at earlier

stages of dysglycemia^{19–21}. This stage is referred to as prediabetes or high risk of diabetes and is defined by fasting plasma glucose levels between 6.1–6.9 mmol/L, 2-hour plasma glucose levels between 7.8–11.0 mmol/L (WHO criteria), and HbA1c levels between 5.7–6.4% (39–47 mmol/mol) (ADA criteria)¹⁷. In parallel with the growing prevalence of T2D, the prevalence of prediabetes is also on the rise.⁹

Risk factors for progression to T2D and its complications range from genetic predisposition to lifestyle and socio-environmental factors. The most common risk factor for diabetes is obesity, and in particular central obesity.²² The accumulation of diabetes risk factors is linked with a combination of adverse changes in cardiovascular disease (CVD) risk factors, including increases in low-density lipoprotein (LDL) cholesterol, triglycerides, and systolic blood pressure, along with decreases in high-density lipoprotein (HDL) cholesterol.²³

Diabetes increases the risk of both microvascular and macrovascular complications, which are major contributors to the morbidity and mortality associated with the disease¹⁵. Beyond conventional CVD risk factors, chronic hyperglycemia promotes the formation of harmful byproducts such as reactive oxygen species and advanced glycation end products, which drive oxidative stress and inflammation²⁴. These processes contribute to endothelial dysfunction and vascular damage.²⁴ While the general mechanisms underlying macrovascular complications are well described, the identification of preclinical stages of CVD and the differentiation of CVD risk between individuals at high risk of diabetes and those with established T2D require further clarification.¹⁰

2.2 Cardiovascular disease

Globally, CVD remains the leading cause of death. At the population level, CVD risk is primarily attributable to modifiable lifestyle behaviors such as chronic stress, physical inactivity, unhealthy diet, excessive alcohol consumption, and smoking, as well as socio-environmental factors like socio-economic status and air pollution.²⁵ At the individual level, these exposures often manifest through more proximal biological risk factors, including hypertension, hypercholesterolemia, diabetes, and obesity.²⁶ Along the causal pathway, these intermediate conditions tend to cluster, thereby accelerating disease progression. These processes are underpinned by biomolecular mechanisms, including local and systemic inflammation, oxidative stress involving oxidized low-density lipoprotein (LDL), and dysregulated immune responses mediated by pro-inflammatory cytokines and signaling pathways.²⁷ Risk factors contribute to distinct pathophysiological mechanisms across different types of CVD, involving structural, signaling, inflammatory, and hemodynamic changes within the cardiovascular system.^{27–29} Among these, cellular and molec-

ular signaling pathways play a central role in regulating vascular tone, cardiac function, and inflammatory responses. These processes are closely modulated by the autonomic nervous system through sympathetic and parasympathetic nerve branches.^{30–33}

2.2.1 Arteriosclerosis

Evidence emphasizes the role of vascular aging in early disease development, extending beyond the traditional focus on cardiovascular endpoints.²⁹ Arteriosclerosis, commonly referred to as arterial stiffness, is a hallmark of this process. Biologically, the medial layer of large arteries consists of a structured network of vascular smooth muscle cells together with elastic and collagen fibers, forming functional musculoelastic sheets.³⁴ Arterial stiffness arises from progressive remodeling of the arterial wall.^{29,35} This remodeling is driven by changes in the structural interactions between elastin and collagen fibers, along with functional alterations in vascular smooth muscle cells and the accumulation of calcium and advanced glycation end products.³⁴ Remodeling of the arterial wall increases systolic blood pressure and reduces coronary perfusion, thereby contributing to the development of hypertension and, eventually, cardiovascular disease.³⁶ Additionally, arterial stiffness elevates the pulsatile load on the microcirculation, promoting the progression of chronic kidney disease, vascular dementia, and Alzheimer's disease.²⁹

2.2.2 Atherosclerosis

Atherosclerosis is characterized by the accumulation of cholesterol, lipids, and other substances within the arterial walls, forming plaques that narrow the arteries and reduce blood flow often at specific sites such as the coronary and carotid arteries.³⁷ This chronic process can lead to progressive occlusion of the vessel, contributing to reduced oxygen supply to the heart (ref.), often leading to symptoms of angina.

Atherosclerotic plaques can be classified into stable and unstable types, each with distinct structural characteristics and clinical implications. Stable plaques typically have a thick fibrous cap composed of collagen, a small lipid core, and low levels of inflammation.³⁸ These plaques are less likely to rupture and tend to remain intact over time due to internal remodeling. In contrast, unstable plaques, also known as vulnerable plaques, often contain a large lipid-rich necrotic core, a thin fibrous cap, and infiltration by inflammatory cells such as macrophages.³⁸ A well-recognized subtype of unstable plaque is the thin-cap fibroatheroma, which is particularly prone to rupture. When rupture occurs, the necrotic core becomes exposed to the bloodstream, initiating the formation of a thrombus or blood clot. This acute event can abruptly obstruct the artery, resulting in myocardial infarction (MI).³⁸ Chronic ischemia due to reduced coronary perfusion can

lead to myocardial remodeling, impaired contractility, and electrical instability, thereby increasing the risk of arrhythmias and heart failure.^{39,40}

Myocardial infarction

MI occurs due to the rupture of an atherosclerotic plaque in the coronary arteries, triggering thrombus formation that blocks blood flow.⁴¹ This leads to oxygen deprivation (ischemia) and subsequent myocardial injury or necrosis.⁴¹ If untreated, this process can cause extensive cardiac damage and fatal arrhythmias.⁴¹ Over the past decades, the incidence of MI has declined in high-income countries with a marked reduction in MI-related mortality.⁴² These improvements are largely attributed to a combination of public health initiatives and medical advances. On the public health front, a substantial decrease in smoking prevalence has been the most important lifestyle-related factor contributing to the reduction in CVD.^{43,44} Medically, the improved preventive management of hypertension and hyperlipidemia has reduced the burden of atherosclerotic disease.⁴² In acute care, the widespread adoption of evidence-based interventions such as thrombolytic therapy, percutaneous coronary interventions (including stenting), and coronary artery bypass grafting has improved survival and outcomes following MI.⁴⁵ In T2D, the risk of MI is elevated by 72%, with an approximately threefold risk among patients under 60 years compared to age under 60 without T2D.⁴⁶ Similar to the general population, MI incidence and fatality have declined among people with diabetes.^{47,greggedwardw?}

Stroke

The majority of strokes are ischemic and result from an obstruction in a cerebral artery. The process often begins with the development of atherosclerotic plaques at the carotid artery bifurcation, which can lead to the formation of emboli⁴⁸. These emboli then travel through the bloodstream and eventually lodge in the cerebral arterial tree, causing ischemic stroke⁴⁸. The second main cause is hemorrhagic stroke, which is characterized as a hypertensive small-vessel disease, leading to small lipohyalinotic aneurysms that subsequently rupture, causing intracerebral bleeding.^{49,50} Ischemic stroke remains one of the global leading contributors to mortality and disability.⁵¹ The incidence, prevalence, and cause-specific mortality of stroke remain high but have stagnated, although some declines have been observed in high-income countries.⁵² Individuals with elevated glucose levels, as measured by fasting plasma glucose, OGTT, or HbA1c, have a 26% higher risk of stroke compared to those with normal glucose levels.^{53,54} In T2D, the ischemic stroke risk is elevated almost two-fold compared with individuals without diabetes.⁴⁶

2.2.3 Heart failure

Heart failure develops gradually with age and often accelerates with the progression of T2D. As prevention and treatment of CVD have improved survival in recent years, the

prevalence of heart failure has increased, while the incidence remains stable, but may rise with aging populations.⁵⁵

Heart failure may arise as a consequence of atherosclerosis, arteriosclerosis, or both, contributing to myocardial ischemia, pressure overload, and structural cardiac changes.⁵⁶ Heart failure can be defined hemodynamically as the inability to maintain adequate cardiac output at rest or during exertion, or the ability to do so only with elevated cardiac filling pressures.⁵⁶ It is a complex cardiovascular disease caused by structural and functional changes in the heart musculature, affecting systolic and/or diastolic pumping function.⁵⁶ Heart failure is generally classified into two subtypes: heart failure with reduced ejection fraction (HFrEF) and heart failure with preserved ejection fraction (HFpEF).⁵⁶ Both subtypes involve cardiac remodeling but are defined by left ventricular ejection fraction (LVEF).⁵⁶ HFrEF is defined by an LVEF < 40%, while HFpEF is characterized by an LVEF ≥ 50% along with structural or functional cardiac abnormalities, as assessed by echocardiography.⁵⁶ HFrEF is often a consequence of repeated, non-fatal MIs. These events can leave behind scar tissue in the myocardium, impairing the heart's ability to contract effectively and leading to progressive systolic dysfunction.[@campbell2024]

The most common feature of HFpEF is left ventricular diastolic dysfunction, caused by impaired relaxation and increased stiffness, leading to elevated left atrial pressure and reduced diastolic reserve.⁵⁷ Over the past decades, the prevalence of HFpEF has increased with an aging population and more people living with conditions such as hypertension, diabetes, and obesity.⁵⁸ It is diagnosed based on structural or functional abnormalities identified through echocardiographic measures, such as left ventricular hypertrophy, left atrial enlargement, or elevated filling pressures.⁵⁸ The diagnosis may seem straightforward, but it is often challenging in community settings, as patients frequently present without typical heart failure symptoms (e.g., shortness of breath) and are not routinely assessed with biomarkers like N-terminal pro-B-type natriuretic peptide (NT-proBNP) or brain-natriuretic-peptide (BNP).⁵⁸ As a result, HFpEF is commonly underdiagnosed and consequently detected at more severe stages, leading to hospitalization .[⁵⁸]⁵⁸

2.3 Cardiovascular autonomic dysfunction

The cardiovascular system is regulated by the autonomic nervous system, which influences heart rate and vasoconstriction through the sympathetic and parasympathetic nerves.³² Sympathetic activation increases heart rate and myocardial contractility by stimulating the sinoatrial (SA) node, atrioventricular (AV) node, and ventricular myocardium. In contrast, parasympathetic activation primarily reduces heart rate by directly modulating SA node activity through vagal stimulation.³² It also slows AV nodal conduction, predominantly via the left vagus nerve, thereby prolonging atrioventricular

conduction time.³² Afferently nerves mainly carry sensory information (e.g., baroreceptor input from the carotid sinus and aortic arch) to the brain, which then adjusts efferent autonomic output to regulate arterial tone. Hence, the autonomic nervous system dynamically regulates heart rate and blood pressure to maintain homoeostasis in response to physiological demands, such as rest, stress, eating and physical activity.³²

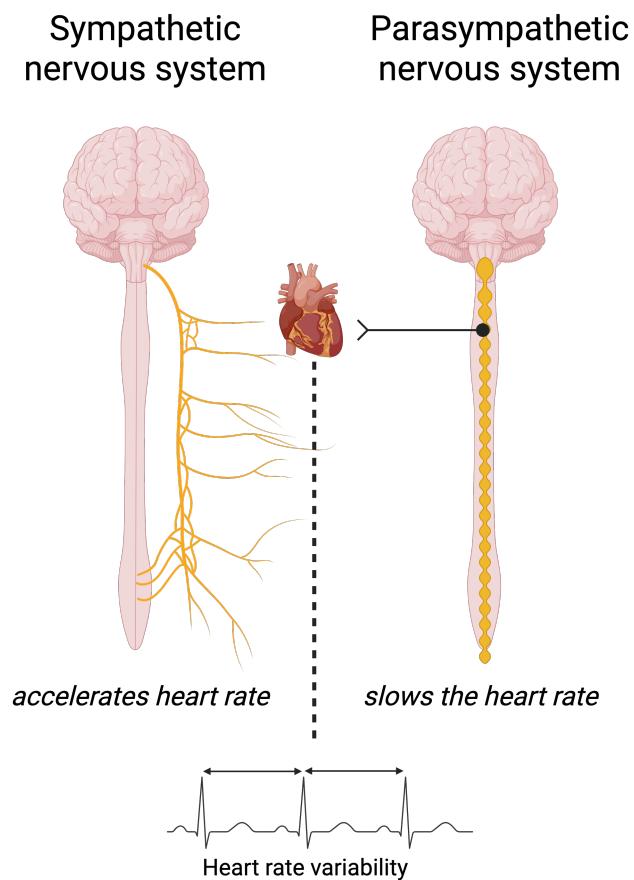


Figure 2.1: Autonomic nervous system and heart rate variability. (Source: Author)

In youth, the autonomic nervous system is highly adaptive and responsive to living conditions, maintaining autonomic balance. However, with aging, there is a gradual decline in parasympathetic function and an increase in sympathetic activity. Additionally, metabolism-related conditions such as obesity and diabetes have been shown to further contribute to cardiovascular autonomic dysfunction (autonomic dysfunction).⁵⁹ Autonomic dysfunction reflects a stressed cardiometabolic environment,

as both dysfunction in lipid and glucose metabolism are associated with increased sympathetic activity.⁵⁹ This dysfunction may result from cumulative neural damage mediated by mechanisms such as hyperinsulinemia, insulin resistance, and elevated levels of adipokines. At the same time, autonomic dysfunction is known to disrupt lipid and glucose metabolism.⁵⁹ Therefore, the relationship between autonomic dysfunction and cardiometabolic factors is likely a vicious cycle.⁶⁰ The consequences can lead to autonomic dysfunction/neuropathy (CAN), resulting in dysregulation in heart rate and vascular dynamics. CAN prevalent in 12-73% in individuals with T2D is linked to CVD diabetic kidney disease, and all-cause mortality.^{[7;61]62} In this dissertation, ‘autonomic dysfunction’ will be used as the broader term, while ‘CAN’ will refer specifically to autonomic dysfunction resulting from neuropathy in diabetes.

Autonomic function can be assessed using heart rate variability (HRV) indices, which measure the variation in successive normal RR intervals in milliseconds. HRV provides time- and frequency-domain estimates of the balance between sympathetic and parasympathetic activity.⁶ High HRV reflects an autonomic nervous system with strong adaptability to the body’s demands, whereas low variation indicates poor adaptation to changing conditions. HRV changes in response to different physiological or environmental conditions (e.g., sleep, stress, posture, physical activity), and these changes can be observed in its natural 24-hour (circadian) pattern.¹³ Most studies have examined autonomic function using short-term ECG recordings at rest.⁵ However, extended HRV recordings across the circadian cycle may offer deeper insights into the influence of lower-frequency variability sources, such as very-low frequency (0.003–0.04 Hz) and ultra-low frequency (0.003 Hz).⁶ HRV has been applied across several research domains. For example, in psychology as a marker of mental stress, in exercise physiology as an indicator of recovery, in cardiovascular research as a marker of autonomic dysfunction due to cardiac complications, and in diabetes research as a marker of autonomic neuropathy.^{7,63–65} T2D alters the expression of sympathetic bursts, as measured by resting muscle sympathetic nerve activity (MSNA). MSNA is elevated in individuals with both T2D and hypertension, compared to those who are normotensive, regardless of whether they have diabetes or not.⁶⁶ Parasympathetic activity is also impaired in individuals with high cardiometabolic risk and T2D, as reflected by reduced baroreflex sensitivity and lower HF and RMSSD short-term HRV.⁶⁷ Before onset of diabetes and during progression of diabetes long-term (24-hour) HRV has shown to be lower compare to those with normal glucose metabolism.^{8,60} Cardiovascular autonomic reflex tests (CARTs) and orthostatic hypotension are considered the gold standard for assessing CAN.⁶⁸ The diagnosis includes assessing pulse rate ratio under test conditions, such as the deep breathing test, the lying-to-standing test, and the Valsalva maneuver.⁶⁸ Both HRV and CARTs have shown to be associated with cardiovascular disease, heart failure, and all-cause mortality, primarily in populations with T2D or established cardiovascular disease.^{[5]61,69} However, it remains unclear at which stage in the progression of diabetes risk to pre-diabetes to

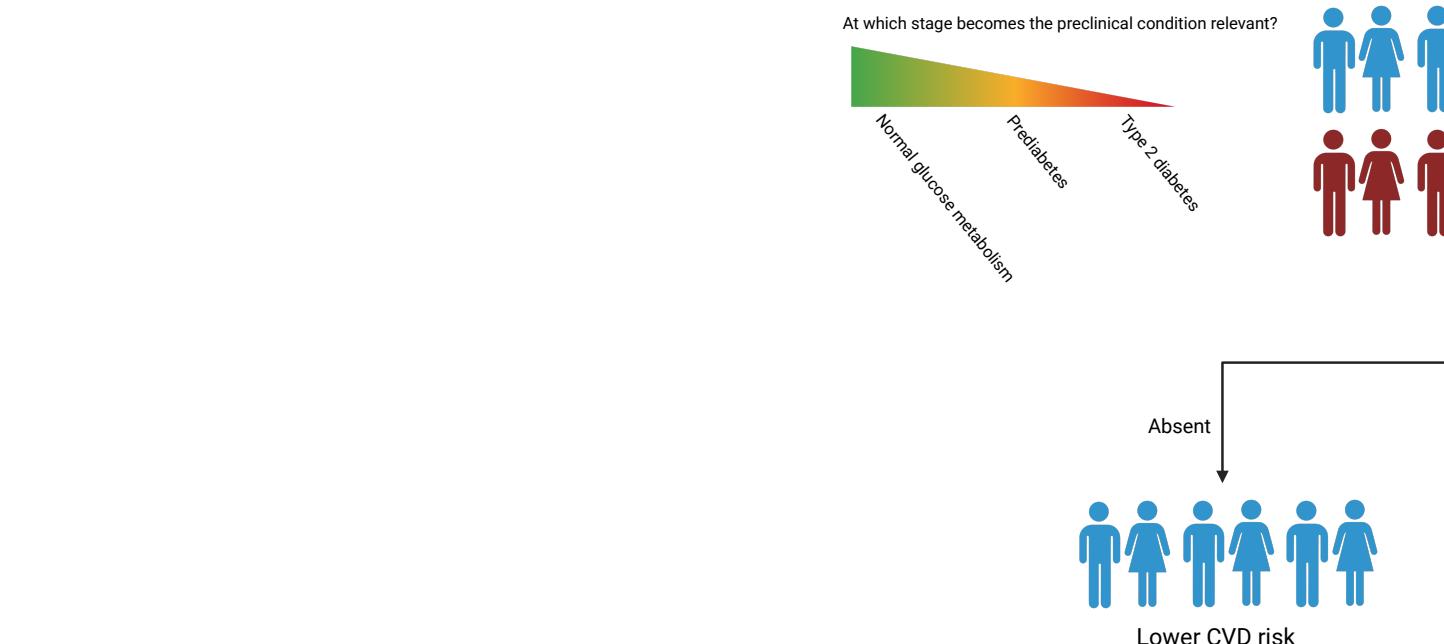
diabetes these measures begin to influence the risk of cardiovascular complications.

2.4 Risk-stratification

Current cardiopreventive guidelines place strong emphasis on prevention and treatment of T2D. The 2022 ADA/EASD guidelines for the management of hyperglycemia in T2D recommend, cardioprotective medication (glucagon-like peptide-1 receptor agonists [GLP-1RA] and Sodium-Glucose Transport Protein 2 [SGLT2] inhibitors) as first-line options for individuals at high cardiovascular risk⁷⁰. Due to their benefits in heart failure, SGLT2 inhibitors are specifically recommended for patients with documented HFrEF or HFpEF. High cardiovascular risk is defined as the presence of at least two risk factors at age >55 years, such as obesity, hypertension, smoking, dyslipidemia, or albuminuria⁷⁰. However, no additional preclinical markers are recommended to identify individuals at higher CVD or HF risk or for younger individuals. Despite their increased risk of cardiovascular complications, individuals at high risk of developing diabetes remain outside structured treatment options, even though diabetes risk and cardiometabolic markers can be successfully modified through lifestyle interventions and medication such as GLP-1 analogues [⁷¹]⁷². During the progression and following the onset of T2D, preclinical indicators of CVD risk become apparent, providing potential opportunities for early risk stratification. Risk stratification is the process of classifying or ranking individuals in increasing order of estimated risk, based on risk scores, biomarker levels, omic data (metabolomic, proteomics, and genomic) or clinical characteristics⁷³. This approach aids in identifying patients at highest risk for further prognostic or diagnostic purposes, identifying subgroups that require further evaluation, intensified treatment, or lifestyle modifications⁷³.

::: {fig-cap=“Conceptual risk-stratification based on preclinical disease.

2.4 Risk-stratification



(Source: Author)

...:

Autonomic dysfunction despite its relationship with cardiovascular complication has not been used in clinical practice in Denmark. Larger epidemiological cohort studies encompassing various stages of diabetes risk, from normal glucose metabolism to prediabetes, onset of T2D, and longer term progression of T2D, serve as valuable resources for identifying risk-stratification opportunities. Epidemiological studies provide a broad representation of the target population, enabling an understanding of the relationship between autonomic dysfunction and cardiovascular complications across different levels of care: public health, primary care, and secondary care. By utilizing observational cohorts, we have the potential to determine when, along the trajectory of diabetes progression, autonomic function becomes a meaningful factor for cardiovascular risk stratification.⁷³

3 Aim and hypothesis

The overarching hypothesis of this dissertation are that:

- CAN and autonomic dysfunction are associated with CVD and act as an early risk factor for heart failure and other cardiovascular complications, including stroke, and myocardial infarction in patients with prediabetes and/or T2D.
- Autonomic dysfunction is associated with higher levels of sub-clinical measures of CVD such as carotid-femoral pulse wave velocity and carotid artery distensibility.

This dissertation investigates the hypothesis by addressing the following three aims:

Study I: Quantify the cross-sectional association between 24-hour HRV and subclinical markers of cardiovascular complications: carotid-femoral pulse wave velocity and carotid artery distensibility, in participants with normal glucose metabolism, prediabetes or T2D.

Study II: Quantify the longitudinal association of multiday and hourly HRV with incidence of ischemic-related CVD, heart failure, and all-cause mortality in a population with high-risk of diabetes.

Study III: Quantify the cross-sectional association between CAN and heart failure. Heart failure will be defined by clinical measures i.e. N-terminal-pro-BNP (NT-proBNP), WATCH-DM risk, and New York Heart Association (NYHA) classification scores among individuals with T2D.

4 Materials and methods

4.1 Overview of the studies

Table 4.1: Table 1: Overview of studies

	Study I	Study II	Study III
Title	Cardiovascular autonomic dysfunction is linked with arterial stiffness across glucose metabolism: The Maastricht Study	Cardiovascular autonomic dysfunction precedes cardiovascular disease and all-cause mortality: 11-year follow-up in the ADDITION-PRO study	Cardiovascular autonomic neuropathy and subclinical heart failure in T2D: The CANCAN study
Design	Aetiological cross-sectional study	Aetiological prospective cohort study	Descriptive cross-sectional study
Cohort	Maastricht study	ADDITION-PRO study	CANCAN study
Study	3673 people with normal glucose metabolism, prediabetes, or T2D	2082 people with high risk of diabetes	173 patients with T2D visiting outpatients clinics
Data	Population-based cohort sources from The Maastricht Study in the Netherlands	Cohort study of selected people based on having high risk of diabetes	Clinical cohort study
Determinant	24-hour HRV	Multiday and hourly HRV	Cardiovascular autonomic reflex test
Primary outcome	Arterial stiffness	Major adverse cardiovascular events, heart failure, and all-cause mortality	NT-proBNP, NYHA classification, and WATCH-DM risk score
Statistical analysis	Linear regression analysis	Poisson regression	Logistic regression

Missing
data

Complete case analysis
Multiple imputation of
chained equations for
confounders

Complete case
analysis and
multiple
imputation of
chained equations
for CART and
confounders

4.1.1 Study population

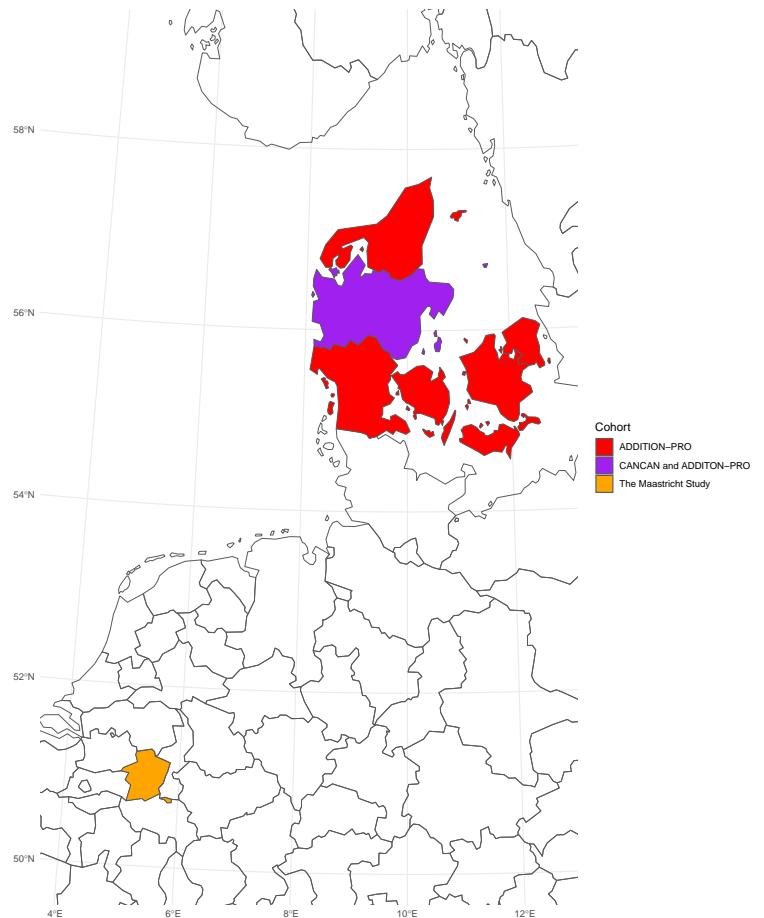


Figure 4.1: Study populations

4.1 Overview of the studies

4.1.1.1 Study I - The Maastricht Study

The Maastricht Study is a prospective observational population-based study of the general population of the province of Limburg, in the southern part of the Netherlands. The study emphasized the recruitment of people with T2D, through the regional Diabetes Patient Registry, to extensively phenotype individuals with T2D and those in intermediate stages of the disease. The eligibility criteria included an age range of 40–70 years. Participants were recruited through mass media campaigns and mailings from municipal registries (Gemeentelijke Basis Administratie; GBA). In the analysis of Study I, the study among 7449 people included participants with measurements of 24-hour HRV and at least one measure of arterial stiffness (carotid-femoral pulse wave velocity or carotid artery distensibility), both of which were completed within a three-month period between November 2010 and December 2020. The study has been approved by the institutional medical ethics committee (NL31329.068.10) and the Minister of Health, Welfare and Sports of the Netherlands (Permit 131088-105234-PG). All participants gave written i⁷⁴

4.1.1.2 Study II - ADDITION-PRO

The ADDITION-PRO study is a prospective, population-based cohort nested within the Danish arm of the ADDITION-Europe study. ADDITION was originally designed as a stepwise screening program for T2D in general practice, aiming to identify individuals with screen-detected T2D for recruitment into the ADDITION trial. ADDITION-PRO aims to investigate early markers of CVD and metabolic dysfunction in individuals in different tiers of diabetes risk.

The ADDITION-Europe screening program identified a large number of individuals with impaired fasting glucose (IFG), impaired glucose tolerance (IGT), and normoglycemia despite having risk factors for diabetes and CVD. Participants for ADDITION-PRO were recruited from the original ADDITION-DK screening cohort, which included individuals from 190 general practices across Denmark. The recruitment strategy focused on individuals at high risk of diabetes without T2D, identified through a stepwise screening program that incorporated the Danish diabetes risk score from the Inter99 study⁷⁵. This assessment, conducted between 2001 and 2006, considered factors such as age, sex, history of gestational diabetes, family history of diabetes, known hypertension, BMI, and physical activity. High-risk individuals were further screened for T2D using blood measurements, including HbA1c, random blood glucose, FPG, and OGTT. Those with screen-detected diabetes, confirmed by a second OGTT, were invited to participate in the ADDITION trial. High risk individuals without T2D were further considered in as the sampling frame for ADDITION-PRO.

Between 2009 and 2011, a follow-up health examination was conducted at four ADDITION-DK study centers to establish a cohort baseline. Eligible participants were those still alive, residing near the research centers (Steno Diabetes Center Copenhagen, Aarhus University Hospital, Holstebro Hospital, and the Hospital of South West Jutland, Esbjerg), and who had not withdrawn consent. Eligibility criteria included individuals aged 40–70 years who had previously undergone diabetes screening in ADDITION-DK. Exclusion criteria included pregnancy, psychological or psychiatric disorders preventing informed consent, and life-limiting conditions. One key feature of the data collection was the precise measurement of physical activity and energy expenditure using a combined chest worn accelerometer/heart rate monitor (ActiHeart), which recorded acceleration and heart rate over a week. In study II, participants with at least a 48-hour recording was included for the primary analysis, and then participants with hourly measures of physical acceleration during the hourly HRV recording was included in the second analysis. Participant with prior CVD ten years before inclusion was also excluded.

Disease history and follow-up data for the population were obtained from Denmark's national registry system, which allows linkage of health records using the personal Civil Registration Number assigned to all citizens. The following national registries were accessed to collect information on incident CVD and mortality, medication use, and healthcare utilization: the National Patient Registry (hospital admissions and outpatient contacts), the National Health Service Registry (general practice visits), the Medical Prescription Registry, the Diabetes Registry, and the Cause of Death Registry.

4.1.1.3 Study III - CANCAN

The CANCAN Study is an observational study conducted at two hospital outpatient clinics in Viborg Regional Hospital and Regional Hospital Gødstrup. It aims to implement a screening protocol for identifying high-risk individuals using CAN assessments, continuous glucose monitoring, and heart failure indicators. All measures were part of routine clinical care for T2D in Central Denmark. We included 200 adults (>18 years) with T2D with a duration of over one year. Exclusion criteria were recent laser-treated eye disease (3 months), pregnancy, lactation, life-threatening illness, or cognitive impairment preventing consent. Participants were identified via electronic records and informed about the study by their doctor during a telephone call. Those interested attended a dedicated meeting before their annual diabetes exam, where study details were discussed. Recruitment took place from 2021 to 2024. In study III, participants without a valid NT-proBNP measurement were excluded.

4.2 Study variables

4.2.1 Measures for autonomic dysfunction/ neuropathy



Figure 4.2: Left: Holter monitor Middle: Actiheart Right: Handheld VagusTM device

Heart rate variability

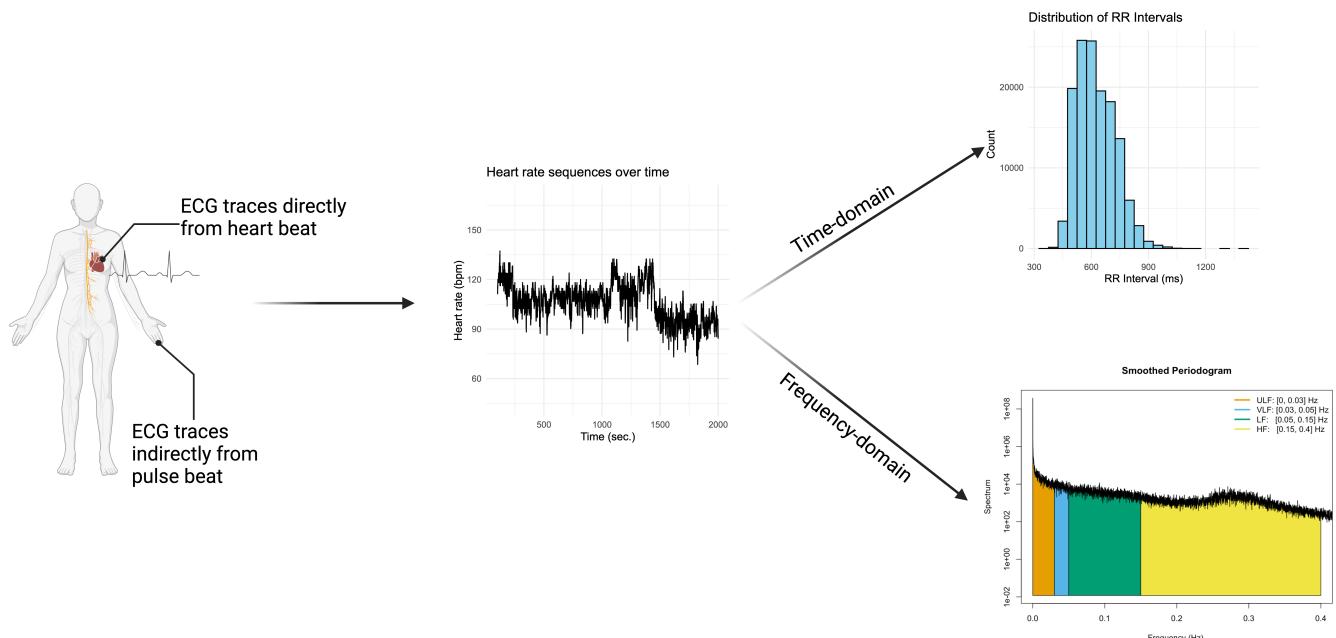


Figure 4.3: Heart rate variability. (Source: Author)

In study I-III different devices were used to capture the distance between each heartbeat defined as RR intervals from electrocardiogram traces either directly from heart-beat traces or indirectly from pulse traces. From this a sequence of successive heart beat intervals is extracted to calculate time- and frequency domain HRV.

Time-domain indices

Time-domain measures of HRV are based on the statistical distribution of normal-to-normal (NN) heartbeat intervals. Description of time-domain indices are summarized in ?@tbl-td.

Frequency-domain indices

Frequency-domain HRV indices are derived from sequences of NN intervals transformed into the spectral domain using Fourier transformation. These indices quantify heart rate oscillations over different timescales. Short-term variations, such as respiratory sinus arrhythmia, reflect rapid autonomic changes, while longer oscillations capture autonomic responses to posture changes, circadian rhythms, or other physiological processes. Description of frequency-domain indices are summarized in ?@tbl-fq.

Holter recordings in study I

All ECG recordings were obtained using a 12-lead Holter system (Fysiologic ECG Services, Amsterdam, the Netherlands) over 24 hours, as previously described. Participants were instructed to follow their regular daily activities but avoid showering during the recording. The ECG data were processed using proprietary Holter Analysis Software (Fysiologic ECG Services), where artefacts and ectopic beats were excluded through automated processing and manual validation. A minimum recording duration of 18 hours was required for further analysis. Inter-beat intervals between consecutive sinus beats were provided in milliseconds (ms). Time-domain HRV indices were calculated, including SDNN, SDANN, RMSSD, SDNN index, and pNN50. Frequency-domain measures were derived using Fast Fourier Transform, including TP, ULF, VLF, LF, and HF. Outliers were removed. HRV indices were standardised by their mean and SD, and composite Z-scores were computed for time and frequency-domain measures, respectively. This selection of indices covers the main sources of HRV variance.

ActiHeart heart rate and physical activity in study II

Heart rate was measured using a combined accelerometer and heart rate monitor (ActiHeart, CamNTech, Cambridge, UK), recording uniaxial acceleration and heart rate. The data collection and processing methods have been described previously. Mean heart rates were recorded in 30-second epochs, and HRV was derived as the variation between consecutive normal heartbeats on the ECG. HRV calculations were performed using the RHRV package (version 4.2.7) in R, including SDNN, SDANN, SDNN index, TINN, and mean HR (mHR). We tested our approach on a dataset with full access to all interbeat

4.2 Study variables

Table 4.2: **Box 1** Time-domain indices reflections of autonomic function

Time-domain HRV	Description
Standard deviation of NN heart beat intervals (SDNN, in ms)	Measures the total variation in interbeat intervals and reflects both sympathetic and parasympathetic activity ⁶ .
SD of the averages of NN intervals in 5-minute segments throughout the recording (SDANN, in ms)	Measures variations in 5-minute mean interbeat intervals, primarily reflecting autonomic fluctuations associated with the circadian rhythm ⁶
Mean of the SDs of all NN intervals for all 5-minute segments (SDNN index, in ms)	Measures the average short-term variability in interbeat intervals across successive 5-minute periods, reflecting both sympathetic and parasympathetic modulation of heart rate ⁶
NN50 count divided by the total number of all NN intervals (pNN50, percentage)	Measures the proportion of successive interbeat intervals differing by more than 50 ms, primarily reflecting parasympathetic (vagal) activity ⁷⁶ .
Square root of the mean of the sum of squares of differences between adjacent NN intervals (RMSSD, in ms)	Measures variation in successive interbeat intervals during inhalation and exhalation, primarily reflecting parasympathetic (vagal) activity ⁷⁶

Table 4.4: **Box 2** Frequency-domain indices reflections of autonomic function

Frequency domain HRV	Description
Variance of all NN intervals 0.4 Hz, total power (TP, in ms²)	Measures the total variation in interbeat intervals, reflecting both short- and long-term autonomic regulation by the sympathetic and parasympathetic nervous system ⁶ .
Ultra low-frequency range (ULF, in ms²; 0.003 Hz)	Measures very long-term oscillations in interbeat intervals, influenced by autonomic responses to circadian rhythms, physical activity, metabolic processes, and thermoregulation [77] ⁷⁸ .
Very-low-frequency range (VLF, in ms²; 0.003–0.04 Hz)	Measures oscillations in interbeat intervals over 5-minute periods, reflecting the activity of the renin–angiotensin system and peaks in sympathetic nervous system activity, while also depending on parasympathetic modulation ^{[79]80} .
Low-frequency range (LF, in ms²; 0.04–0.15 Hz)	Measures intermediate oscillations in interbeat intervals, reflecting a combination of sympathetic and parasympathetic nervous system activity, particularly associated with baroreflex function and blood pressure regulation ⁸¹ .
High-frequency range (HF, in ms²; 0.15–0.4 Hz)	Measures short-term oscillations during inspiration and expiration, reflecting parasympathetic modulation of heart rate via the vagus nerve, and closely associated with respiratory sinus arrhythmia ⁸² .

4.2 Study variables

intervals to validate our algorithm⁸³. These indices have shown high validity for HRV indices based on global distribution (e.g. SDNN, SDANN, SDNNi) in 24-hour recordings. HRV indices were calculated by week, 24-hour cycle, and hour of the day, with hourly values averaged across recording days.

Vagus device for cardiovascular autonomic reflex test in study III

CAN was diagnosed using cardiovascular autonomic reflex tests (CARTs), the gold standard for CAN assessment. R-R intervals were derived from an ECG signal using the Vagus™ device (Medicus Engineering, Aarhus, Denmark)⁶⁸. We used pulse rate ratios measured under different conditions. Three standardized cardiovascular autonomic reflex tests (CARTs) were performed: (1) lying-to-standing, (2) deep breathing, and the (3) Valsalva manoeuvre, following a standardized protocol conducted between 8:00 a.m. and 2:00 p.m., after 10 minutes of supine rest. Smoking and caffeine intake were prohibited two hours before testing. Each test was conducted once by trained examiners.

Manifest CAN was defined as two or more abnormal CARTs using age-specific cut-off values (ref.). The Vagus™ device's accuracy has been validated against FDA standards and stationary devices, showing moderate to high reproducibility (ref.). Orthostatic hypertension was defined as a sustained drop in systolic blood pressure of 20 mmHg or diastolic blood pressure of 10 mmHg within three minutes of standing (ref.).

Cardiovascular autonomic reflex test



Figure 4.4: CART

4.2.2 Confounders and variables for instrumental bias

Across Studies I, II, and III, a comprehensive set of covariates and potential confounders were assessed, including lifestyle factors, clinical measurements, biochemical markers, and socioeconomic indicators.

Smoking status was self-reported in all studies, categorized as never, former, or current (Study I), current/ex/never (Study II), and smoker/non-smoker (Study III). Alcohol

consumption was recorded as average weekly units in all three studies. Physical activity was assessed via self-report in Studies I, II, III, with Study I capturing total and moderate-to-vigorous activity (hours/week), Study II used the Recent Physical Activity Questionnaire (RPAQ) to calculate physical activity energy expenditure (PAEE), and Study III classifying activity as sedentary or non-sedentary. In Study II also used combined accelerometry and heart rate monitoring (ActiHeart) to estimate PAEE. Study II included register-based data on socioeconomic status at baseline, including education length, income, and employment status. All studies included measurements of body mass index (BMI), waist circumference, and systolic and diastolic blood pressure, obtained during clinical examinations.

Blood samples were analyzed in all studies for HbA1c, fasting plasma glucose (FPG), triglycerides, total cholesterol, high-density lipoprotein (HDL), and low-density lipoprotein (LDL) cholesterol. Study I also included a 2-hour oral glucose tolerance test (OGTT) to classify glucose metabolism status based on FPG and OGTT (normal, prediabetes, T2D) using WHO 2006 criteria, excluding HbA1c as a diagnostic criterion. Study III additionally measured creatinine, estimated glomerular filtration rate (eGFR), and urine albumin-to-creatinine ratio.

Self-reported history of CVD and use of anti-hypertensive, glucose-lowering, and lipid-lowering medications were collected in all studies. In Study II, history of CVD events in the 10 years prior to baseline were retrieved from national registers. In Study III, history of CVD was collected electronic patient records.

4.3 Outcomes

4.3.1 Arterial stiffness

Arterial stiffness is characterized by arteriosclerosis and atherosclerosis properties of the arteries. The stiffness of different segments of the vascular musculature can be assessed both locally and dynamically. Aortic and carotid stiffness were assessed as markers of arterial stiffness, following previously described procedures⁸⁴.

Pulse wave velocity

Aortic stiffness was measured by carotid-femoral pulse wave velocity (cf-PWV) using applanation tonometry (SphygmoCor, Atcor Medical, Sydney, Australia), with the median of at least three consecutive recordings included in the analysis. cf-PWV is calculated based on the time between the ECG systole and the arrival of the pressure wave at the femoral and carotid measurement sites along with the distance between these two measurement sites. cf-PWV is measured with participants in a supine position following

a 10-minute rest period. The aortic path length was determined using a tape measure by subtracting the carotid-to-sternal notch distance from the femoral-to-sternal notch distance⁸⁴.

Carotid artery distensibility

Carotid stiffness was assessed by the carotid artery distensibility coefficient (CD), based on ultrasound imaging of the left common carotid artery using a 7.5 MHz linear probe (MyLab 70, Esaote Europe, Maastricht, the Netherlands). CD was calculated as $\Delta D/\text{braPP}$, where ΔD represents carotid distension and braPP is brachial pulse pressure. Mean heart rate and mean arterial pressure (MAP) were recorded every five minutes using an oscillometer device (Accutorr Plus, Datascope, Montvale, NJ, USA)⁸⁴.

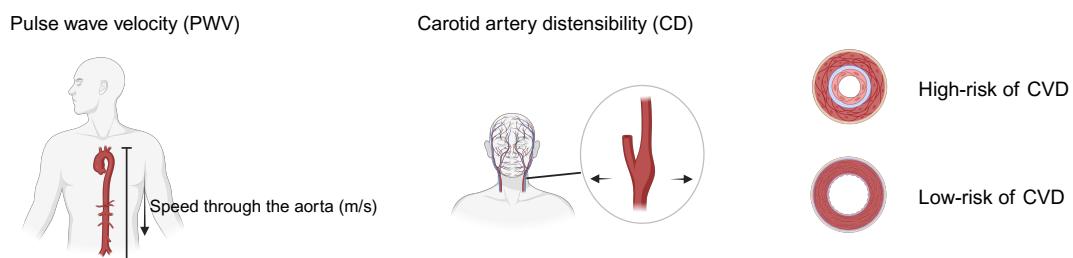


Figure 4.5: Measures of arterial stiffness, measured dynamically at the aortic and local carotid sites. (Source: Author)

4.3.2 Indicators of heart failure

N-terminal prohormone of brain natriuretic peptide (NT-proBNP) is a neuretic peptide that can be used to detect patients with heart failure and the progression of heart failure. It derives from B-type natriuretic peptid (BNP) which is a cardial neurohormone, that is synthesized and secreted as response to stretched cardiomyocytes and cardiac volume overload. After secretion, proBNP is cleaved, releasing the active hormone BNP along with the remaining N-terminal fragment, known as NT-proBNP. In Study III, a blood sample was taken at the study cite. Description of the NT-proBNP analysis of plasma samples is described in supplementary material [ref.].

A modified version of the validated The WATCH-DM heart failure risk score was used. The risk score is based on 9 variables: two binary (history of myocardial infarction and coronary artery bypass grafting) and seven continuous (age, BMI, systolic/diastolic BP, serum creatinine, HDL cholesterol, and HbA1c). Scores range from 0–39, categorized as very low (11), low (12–13), moderate (14–15), high (16–18), and very high (19) risk.

Table 4.6: ?(caption)

Outcome	Diagnosis codes
<i>Heart failure</i>	ICD: I50
<i>Three-point MACE</i>	
• Stroke	ICD: I61 - I64
• Myocardial infarction	ICD: I21-I24
• Cardiovascular death	ICD: I20-I28, I42, I46
• Cardiovascular revascularization	SKA: KPAE10, KPAE25, KPAF10, KPAF20, KPAF21, KPAF22, KPAH10, KPAH20, KPAH21, KPEE, KPEF, KPEH, KPEP, KPEQ, KPFE,, KPFH, KPFP, KPFQ

NYHA class stage I-IV was included. Heart failure symptoms were defined as NYHA class II-IV, assessed by a physician.

4.3.3 Cardiovascular events

Information on CVD events and mortality was obtained from the Danish National Patient Registers until 2021 by utilizing the ICD-10 codes for stroke, myocardial infarction, cardiovascular death, cardiovascular revascularization, and heart failure. We defined three-point major adverse cardiovascular events (MACE) as myocardial infarction, stroke, cardiovascular revascularization, and cardiovascular death.

4.4 Statistical Methods

4.4.1 Cross-sectional analysis

Study I

In Study I, we used multiple linear regression to investigate associations between multiday HRV and arterial stiffness. Model 1 adjusted for age, sex, education, glucose metabolism status, and mean arterial pressure (MAP) to account for the oversampling of individuals with T2D and potential instrumental bias of arterial pressure flow. Model

4.4 Statistical Methods

2 included additional adjustments for smoking behavior, alcohol consumption, physical activity, body mass index, HbA1c, triglycerides, total-to-HDL cholesterol ratio, and medication use. Arterial stiffness measures were log-transformed to ensure normally distributed residuals and back-transformed into percentage change estimates. A sex interaction term was added to assess if the association differed between sex. We performed sensitivity analyses excluding individuals on antihypertensive treatment or glucose-lowering medication. We performed sensitivity analyses excluding individuals on antihypertensive treatment or glucose-lowering medication.

Study III

In Study III, we applied logistic regression models to investigate the association between CAN and heart failure, using NT-proBNP as the primary outcome. We adjusted for age, sex, and diabetes duration, smoking behavior, alcohol consumption, body mass index, HbA1c, triglycerides, total cholesterol, and antihypertensive medication, eGFR and prior CVD. We performed sensitivity analyses and excluded participants with beta-blocker treatment or prior CVD. We applied logistic regression to assess the odds of CAN association with heart failure symptoms, defined by a NYHA class II or higher, adjusting for covariates in primary analysis. Linear regression was employed to evaluate differences in the WATCH-DM risk score between individuals with and without CAN.

4.4.2 Time-to-event analysis

In Study II, we used Poisson regression models to quantify the associations between HRV and cardiovascular events, as follow-up data were undisturbed over time and to avoid assumptions of proportional hazards⁸⁵. Multiday HRV was modelled using splines with knots at predefined percentiles to assess non-linear associations. Hourly HRV was analysed separately for each hour to observe if the association of HRV had diurnal variation. Both HRV and mHR were standardized by their mean and standard deviation to ensure comparability. Based on assumptions about potential confounding pathways summarized in directed acyclic graphs (DAG), we fitted two models: Model 1 adjusted for age and sex, while Model 2 further adjusted for education, smoking, alcohol consumption, physical activity (physical activity energy expenditure (PAEE) calculated from Recent Physical Activity Questionnaire RPAQ), body mass index, total cholesterol, and HbA1c. Additional analyses were performed with HRV pre-adjusted for concurrent heart rate and physical acceleration to account the influence of these factors. Missing covariates were handled using multiple imputation. Each individual's follow-up period began at the time of their inclusion in the baseline examination. To calculate age-specific incidence rate (IR) we did the following. Follow-up ended at the earliest occurrence of CVD, heart failure, all-cause mortality, death, or the end of the study period . The follow-up time was divided into one-year intervals based on the individual's age. Using this age-split

data, incidence rates of CVD, heart failure, and all-cause mortality were analyzed in relation to the HRV, with age treated as a time-varying covariate in a Poisson regression model.

4.4.3 Effect modification

Effect modification is used to assess whether the association between an exposure and an outcome varies depending on the level of a third variable, known as the effect modifier⁸⁶.

In Study I, it was hypothesized that the association between 24-hour and arterial stiffness was stronger in strata of progression of diabetes (normal glucose metabolism, prediabetes, T2D). Therefore, interaction term between HRV and diabetes status was included to observe the size of the association across strata. We did subsidiary analysis in a sub-population without T2D to check if the effect was modified by HbA1c. In Study II, the association between multiday HRV and CVD endpoints varied by sex was quantified, to explore potential biological dimorphism. In Study III, we aimed to determine whether the association between CAN and elevated NT-proBNP is present in the subgroup without symptoms, defined as NYHA class < II. Hence, the hypothesis was no significant effect modification between groups with and without symptoms. Similarly, whether the association remains present in the group classified as low to moderate risk of heart failure was explored, based on the WATCH-DM risk score.

A significant effect modification between the exposure and the effect modifier in all analyses was defined as an interaction term with a p-value < 0.05.

4.4.4 Multiple imputed by chained equations

Multiple Imputation by Chained Equations (MICE) is a method for handling missing data in datasets. This procedure imputes missing values through an iterative series of predictive models, generating plausible estimates while preserving the relationships within the data. To avoid one imputation for missing value could give the value the same confidence as the a non-missing value, Rubins Rule was followed. Rubin's rules in MICE combine results from multiple imputed datasets by pooling estimates of interest (e.g., means or regression coefficients) using their within- and between-imputation variances. Thus, we ensure valid statistical inferences by accounting for the uncertainty introduced by missing data.

In Study II, confounders was imputed to include as many participants and avoid excluding population with our without cardiovascular or mortality events. Dataset was

imputed 10 times. In Study III, missing CART was imputed, as a proportion of participants had non-valid test due to insufficient air in the valsalva manuevre, unstable heart beats or data error. These variables was used as auxiliary variables in imputation to reduce bias⁸⁷. All available variables of biochemical measures, diagnosis, medication and cause of non-valid CART was used to impute each missing CART using predictive mean matching.

4.4.5 Instrumental bias

In Study I-III we are investigating the body properties by dynamic measures and biomarkers to quantify autonomic function, arterial stiffness, and cardiac function. Other conditions may affect the properties we are attempting to measure, and thus are causing instrumental bias.

Vascular Stiffness

In Study I, we used measurements of arterial stiffness using cf-PWV and carotid distensibilty. Both measures are influenced by arterial pressure at the time of examination. Arterial pressure affects the propagation of the pressure wave through the aorta (cf-PWV) and the expansion and contraction of the carotid artery (carotid distensibilty) [ref.]. To account for this, we adjusted for mean arterial pressure in our models.

Cardiovascular autonomic function

In Study II, we assessed autonomic function using multiday HRV recordings and hourly HRV measurements. Studies have highlighted that HRV is dependent on heart rate, and low HRV may simply reflect a higher resting heart rate (rHR). To adjust for this without overcorrecting for a collinear variable, we pre-adjusted HRV by regressing rHR on HRV, extracting the residuals, and using these as the pre-adjusted determinant. For hourly HRV, variability in heart rate may be influenced by changes in physical activity, creating a risk that HRV serves as a proxy for movement rather than autonomic function. To address this, we applied a similar pre-adjustment approach by regressing concurrent heart rate and physical acceleration to account for physical activity.

Biomarker of Heart Failure

In Study III, kidney function and overweight are know to influence NT-proBNP levels independently of heart failure⁵⁶. We adjusted the model to account for the blurred effect of eGFR on NT-proBNP levels in the analysis.

5 Results

5.1 Study I

Table 5.1: Study characteristics by diabetes status

Characteristic	**Normal glucose metabolism** N = 2,389	**Prediabetes** N = 538	**Type 2 Diabetes** N = 746
Sex			
Men	1,028 (43%)	280 (52%)	481 (64%)
Women	1,361 (57%)	258 (48%)	265 (36%)
Age (years)	58 (51, 64)	62 (57, 68)	63 (57, 68)
Total physical activity (hours/week)	13 (9, 19)	13 (9, 19)	12 (7, 17)
Moderate to vigorous physical activity (hours/week)	5.3 (3.0, 8.3)	4.5 (2.3, 7.5)	3.8 (1.5, 6.8)
BMI (kg/m ²)	25.0 (22.9, 27.4)	27.2 (24.9, 30.1)	28.8 (26.0, 31.7)
Waist (cm)	89 (81, 97)	98 (90, 105)	103 (96, 112)
HbA1c (%)	5.35 (5.17, 5.63)	5.63 (5.35, 5.90)	6.54 (6.08, 7.09)
Fasting plasma glucose (mmol/L)	5.10 (4.80, 5.40)	5.90 (5.40, 6.30)	7.40 (6.60, 8.50)
LDL (mmol/L)	3.20 (2.70, 3.90)	3.30 (2.60, 4.00)	2.40 (1.80, 3.10)
HDL (mmol/L)	1.60 (1.30, 2.00)	1.40 (1.20, 1.80)	1.30 (1.00, 1.50)
Total cholesterol (mmol/L)	5.50 (4.80, 6.20)	5.50 (4.80, 6.30)	4.50 (3.90, 5.20)
Triglycerides (mmol/L)	1.05 (0.80, 1.45)	1.39 (1.03, 1.90)	1.51 (1.08, 2.14)
Duration of type-2 diabetes (only for diagnosed participants)	NA (NA, NA)	NA (NA, NA)	3 (0, 9)
Mean IBI (ms)	838 (775, 907)	815 (760, 897)	806 (744, 889)
SDNN (ms)	138 (117, 164)	127 (106, 152)	116 (96, 139)
RMSSD (ms)	26 (21, 34)	24 (19, 33)	22 (17, 31)
SDANN (ms)	125 (103, 149)	113 (92, 139)	103 (84, 127)
SDNNi (ms)	55 (46, 65)	50 (41, 60)	44 (36, 54)
pNN50 (%)	7 (3, 13)	5 (2, 10)	4 (2, 9)
TP (ms ²)	12,596 (8,880, 17,498)	10,615 (7,134, 15,374)	8,880 (6,064, 12,722)
ULF (ms ²)	10,771 (7,392, 15,142)	8,948 (5,852, 13,374)	7,524 (5,036, 11,001)
VLF (ms ²)	1,198 (833, 1,692)	1,015 (685, 1,478)	816 (541, 1,267)
LF (ms ²)	421 (257, 651)	328 (200, 540)	261 (154, 422)
HF (ms ²)	94 (57, 158)	78 (47, 138)	63 (36, 117)
Systolic blood pressure (mmHg)	123 (114, 133)	129 (122, 140)	130 (122, 139)
Diastolic blood pressure (mmHg)	75 (71, 80)	78 (73, 83)	76 (72, 81)
Mean arterial pressure (mmHg)	95 (88, 102)	99 (93, 107)	98 (92, 105)
Carotid artery distensibility (10-3/kPa)	15.0 (11.8, 18.8)	13.5 (10.4, 16.9)	12.5 (9.9, 16.0)
Carotid-femoral pulse wave velocity (m/s)	8.08 (7.28, 9.16)	8.96 (7.84, 10.32)	9.36 (8.16, 10.80)
N-HT	833 (35%)	317 (59%)	590 (79%)
Antihypertensive medication	431 (18%)	199 (37%)	478 (64%)
med-HT_beta	149 (6.2%)	77 (14%)	195 (26%)
Lipid-lowering medication	280 (12%)	141 (26%)	484 (65%)

In this section, study population characteristics and findings from analysis will be presented.

5.1 Study I

5.1.1 Descriptive

In The Maastricht Study, [10,000 participated by Date], of those 1316 reported prior CVD⁷⁴. Participants who had valid 24-hour HRV measured was 4379 and of those 3673 had a valid measurement of either CD or cf-PWV. Study population included 3673 participants. Further characteristic are described in the study in manuscript Table 1 in appendix⁷⁴.

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Categorical variables: n (%) Continuous variables: Median (IQT range 25thh – 75thh)

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5.1.2 24-hour HRV and arterial stiffness

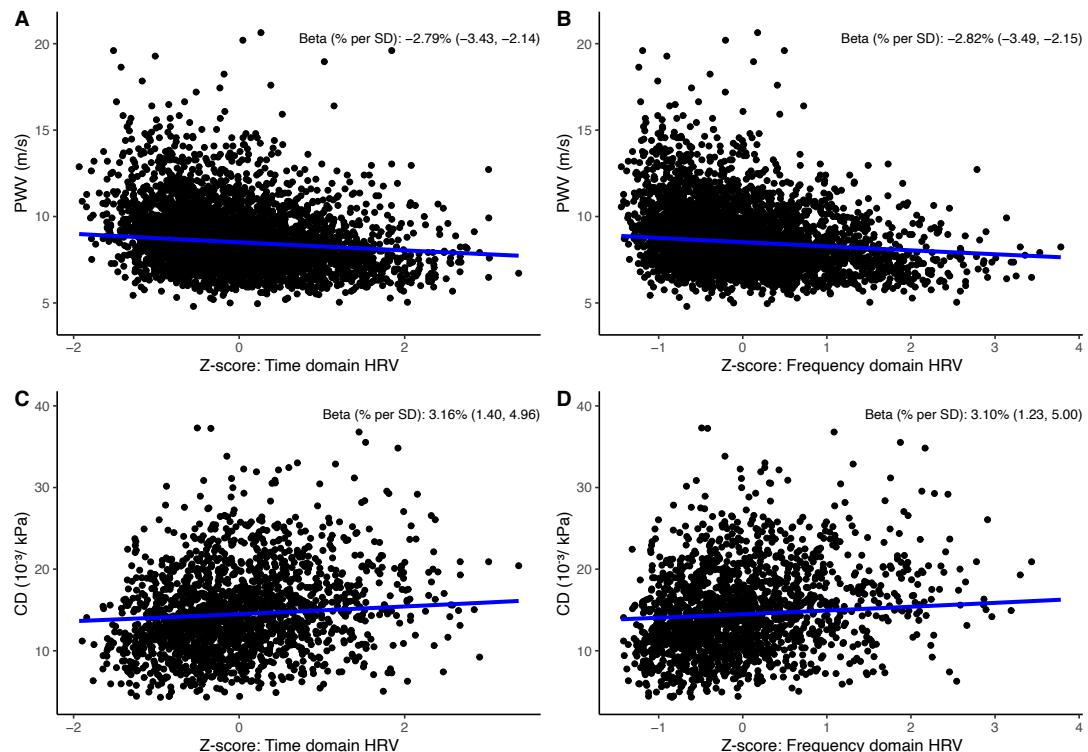
Time-domain HRV

In the fully adjusted model 2, cf-PWV was 2.8% (CI: 2.1; 3.4) lower, while CD was 3.3% (CI: 1.5; 5.1) higher per SD higher in HRV time-domain Z-score (see see ?@fig-MS-HRV_overall A and B). Among the time-domain indices, SDNN, SDNNi, and SDANN showed the strongest associations, with cf-PWV being lower by 2.5% (CI: 2.0; 3.1), 2.5% (CI: 1.9; 3.4), and 2.2% (CI: 1.7; 2.7), respectively⁷⁴. Conversely, CD was higher by 3.2% (CI: 1.7; 4.7), 3.0 % (CI: 1.4; 4.6), and 2.8% (CI: 1.3; 4.3), respectively. RMSSD and pNN50 showed a weaker association with cf-PWV (-1.1% [CI: -1.4; -0.4], and -1.1 [-1.7; -0.6]), while no evidence for an association was found with CD⁷⁴.

Frequency-domain HRV

In the fully adjusted model 2, cf-PWV was 2.8% (CI: 2.1; 3.5) lower, while CD was 3.2% (CI: 1.3; 5.1) higher per SD higher in HRV frequency-domain Z-score (see see ?@fig-MS-HRV_overall C and D). Among the frequency-domain indices, total power, VLF, and ULF showed the strongest associations, with cf-PWV being lower by 2.2% (CI: 1.7; 2.8), 2.4% (CI: 1.9; 4.0), and 2.1% (CI: 1.5; 2.6), respectively⁷⁴. Conversely, CD was higher by 2.7% (CI: 1.2; 4.2), 2.4% (CI: 0.9; 4.1), and 2.6% (CI: 1.1; 4.1), respectively. HF showed a weaker association with cf-PWV (-0.9% [CI: -1.4; -0.4]), while no evidence for an association was found with CD. Mean interbeat interval was associated with 2.4 % (CI: 1.8; 2.9) lower cf-PWV and 4.5% (3.1; 6.1) higher CD⁷⁴.

5.1 Study I



A: Percentage PWV per SD in time-domain composite z-score B: Percentage PWV per SD in frequency-domain composite z-score C: Percentage higher CD per SD in time-domain composite z-score D: Percentage CD per SD in frequency-domain composite z-score. All regression lines were adjusted for being a male, 60 years old, low educational level, without prediabetes or type-2 diabetes, and with 96mmHg mean arterial pressure. From Figure 1 in Appendix Study I⁷⁴

Figure 5.1: Association between HRV and arterial stiffness

5.1.3 Effect modification of diabetes status

The study population represented diabetes risk of normal glucose metabolism (65%), prediabetes (15%), and T2D (20%). The median (IQR) cf-PWV (aortic stiffness) became higher with diabetes status: NGM: 8.08 m/s (7.28, 9.16), prediabetes: 8.96 m/s (7.84, 10.32), and T2D: 9.36 m/s (8.16, 10.80). CD (carotid stiffness) decreased: NGM: 15.0 (11.8, 18.8), prediabetes: 13.5 (10.4, 16.9), and T2D: 12.5 (9.9, 16.0) $\times 10^3$ /kPa. SDNN (ms) was highest in NGM and lowered with worsening glucose metabolism: NGM: 138ms (117, 164), prediabetes: 127ms (106, 152), and T2D: 116ms (96, 139). Further description of characteristics by diabetes are described in Table ??.

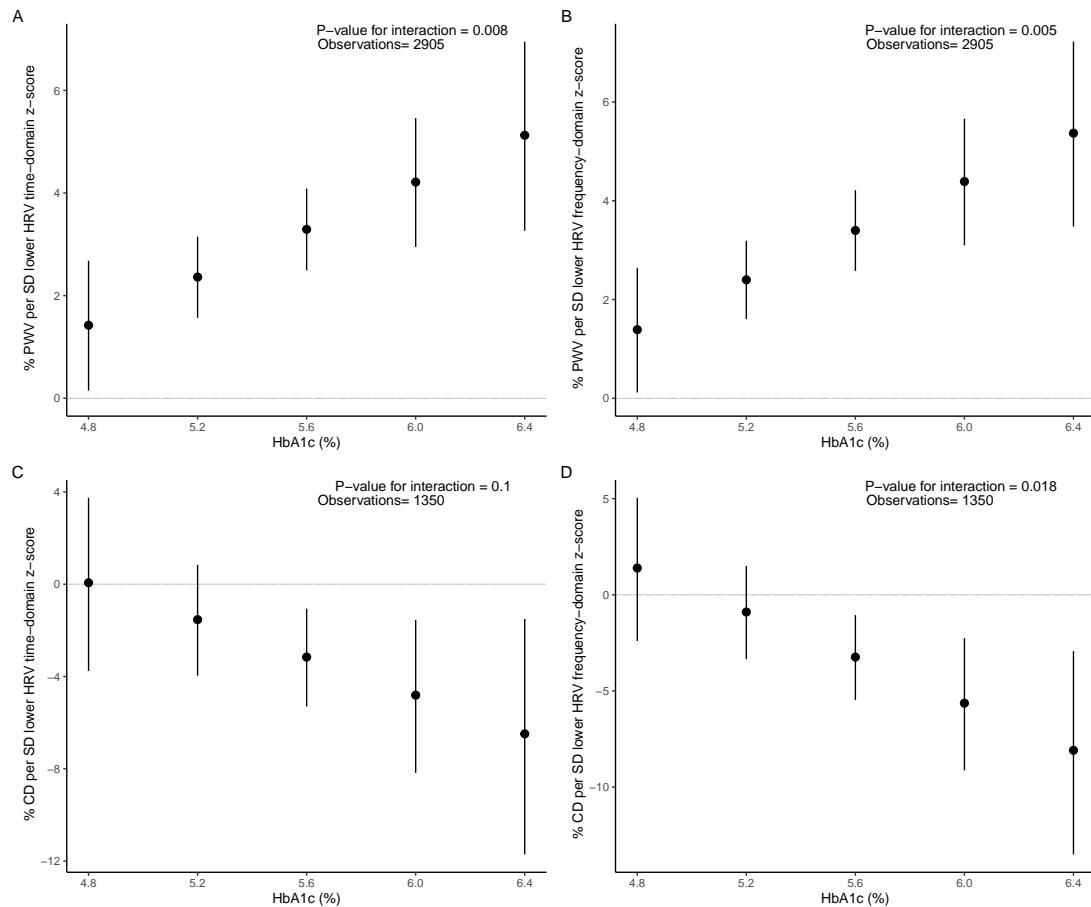
5 Results

The association between HRV time-domain Z-scores and cf-PWV and CD was significantly modified by prediabetes (cf-PWV: -4.9 [CI: -6.523; -3.243] $\text{interaction}(*\text{p-value}<0.01)$ CD: 8.0 [CI:3.8; 12.5] $^{*\text{p-value}<0.01}$) but not by T2D (cf-PWV: -3.5 % [CI: -4.8; -2.1]) $^{*\text{p-value}<0.1}$ CD: 4.8 % [CI:1.3; 8.4] $^{*\text{p-value}<0.1}$)⁷⁴. For the indices SDNN and SDANN, the association with both cf-PWV and CD was significantly modified by both prediabetes and T2D⁷⁴.

The association between HRV frequency-domain Z-score and cf-PWV was significantly modified from normal glucose metabolism by prediabetes (-5.7 %[CI:-7.4; -3.9] $^{*\text{p-value}<0.01}$) and T2D (-3.9 %[CI:-5.4; -2.3] $^{*\text{p-value}<0.05}$) while CD was only modified by prediabetes (8.3 %[CI:3.6; 13.2] $^{*\text{p-value}<0.01}$) but not by T2D (5.3 %[CI:1.4; 9.4] $^{*\text{p-value}<0.1}$)⁷⁴. For the indices total power and ULF, the association with both cf-PWV and CD was significantly modified by both prediabetes and T2D. Mean inter beat interval association with cf-PWV or CD was not significantly modified by diabetes status⁷⁴.

As no stepwise increase was observed in the modification of glucose metabolism status from prediabetes to T2D, subgroup with T2D was excluded to test whether the association was gradually modified by dysglycemia. In this subgroup, the association between HRV time and frequency domain Z-scores and measures of arterial stiffness was modified by HbA1c (range of interaction p-values: 0.1 to 0.005) (see Figure ??). For example, per SD lower HRV frequency domain Z-score at HbA1c 6.4% was associated with a 5.4% higher (CI: 3.5; 7.2) cf-PWV, which was 2.0% to 4.0% higher compared to the magnitude of association at HbA1c levels of 5.6% and 4.8% (see Figure ?? B). In CD, per SD lower HRV frequency domain Z-score at HbA1c 6.4% was associated with an 8.1% lower (CI: -13.5; -2.9) CD, which was 4.8% to 9.5% lower compared to the magnitude of association at HbA1c levels of 5.6% and 4.8% (see Figure ?? D). No association between HRV frequency domain Z-score and CD was observed at HbA1c levels between 4.8% and 5.2%.

5.1 Study I



A: Percentage PWV per SD in time-domain composite z-score B: Percentage PWV per SD in frequency-domain composite z-score C: Percentage higher CD per SD in time-domain composite z-score D: Percentage CD per SD in frequency-domain composite z-score. Model adjusted for sex, age, educational status, diabetes status, and mean arterial pressure, physical activity, smoking behaviour, alcohol use, body mass index, hba1c, triglycerides, total-to-high density lipoprotein cholesterol ratio, lipid-modifying- and antihypertensive medication. Figure was based on data in Study I⁷⁴

Figure 5.2: **Association between HRV and arterial stiffness modified by HbA1c in subpopulation without T2D**

5.2 Study II

5.2.1 Descriptive

The ADDITION-PRO population consisted of 1,627 participant with at least 48-hour HRV measures, while 1,432 had all hour represented with hourly HRV and physical acceleration. The study population included different tiers of diabetes risk: 154 individuals at low risk (9%), 889 at high risk (51%), 314 with impaired fasting glucose (IFG) (18%), 226 with impaired glucose tolerance (IGT) (13%), and 161 with both IFG and IGT (9%). SDNN was splitted into categories by very-low (SDNN< 100 ms), low (SDNN 100-120 ms), middle (SDNN 121-140 ms), high (SDNN 141-160 ms) and very-high (SDNN >160 ms).

Characteristics are described in Table ???. Participants in the lowest SDNN group (<100 ms) were older (67.4 ± 6.9 years), had higher BMI (28.1 ± 5.4), HbA1c (5.9 ± 0.9), triglycerides (1.5 ± 0.9 mmol/L), and resting heart rate (67.8 ± 5.7 bpm), were more likely to use anti-hypertensive medication (61%), and had lower physical activity energy expenditure (46.8 ± 24.0 kJ/day) compared to those with higher SDNN levels.

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Table 5.2: Study participants characteristics

Characteristic	Overall, N = 1,625	<100, N = 148	100-120, N = 312	120-140, N = 457	140-160, N = 346	>160, N = 362
sex						
Men	866 (53%)	68 (46%)	148 (47%)	206 (45%)	203 (59%)	241 (67%)
Women	759 (47%)	80 (54%)	164 (53%)	251 (55%)	143 (41%)	121 (33%)
Age (years)	65.9 (6.8)	67.4 (6.9)	65.7 (6.9)	66.0 (6.7)	65.5 (6.6)	66.0 (7.0)
Physical activity energy expenditure (KJ / day)	53.1 (25.1)	46.8 (24.0)	49.4 (21.0)	50.7 (21.5)	57.6 (27.2)	57.5 (29.2)
Alcohol consumption (units per week)	9.2 (9.5)	11.3 (10.8)	10.2 (11.3)	8.9 (8.5)	8.5 (9.2)	8.7 (8.2)
Smoking status						
1	263 (16%)	40 (28%)	70 (23%)	65 (14%)	41 (12%)	47 (13%)
2	750 (47%)	58 (40%)	145 (47%)	214 (47%)	162 (47%)	171 (48%)
3	598 (37%)	47 (32%)	95 (31%)	174 (38%)	140 (41%)	142 (39%)
BMI (kg/m ²)	27.7 (4.7)	28.1 (5.4)	28.2 (4.6)	28.0 (4.7)	27.7 (4.9)	26.9 (4.2)
Waist circumference (cm)	96.7 (13.4)	98.0 (14.9)	98.2 (13.2)	96.7 (13.6)	96.7 (13.1)	94.8 (12.5)
Systolic blood pressure (mmHg)	133.7 (17.3)	134.2 (16.3)	133.7 (17.6)	133.5 (17.8)	133.4 (16.9)	133.8 (17.5)
Diastolic blood pressure (mmHg)	81.9 (10.4)	83.8 (10.1)	82.7 (10.2)	81.7 (10.6)	82.1 (10.2)	80.6 (10.3)
Pulse rate (bpm)	67.4 (10.9)	77.7 (11.2)	72.6 (9.3)	67.9 (9.3)	65.3 (9.3)	60.0 (9.8)
HbA1c (%)	5.8 (0.5)	5.9 (0.9)	5.9 (0.6)	5.8 (0.5)	5.7 (0.4)	5.7 (0.4)
Triglycerides (mmol/L)	1.3 (0.7)	1.5 (0.9)	1.4 (0.7)	1.3 (0.6)	1.2 (0.7)	1.1 (0.6)
Total cholesterol (mmol/L)	5.4 (1.1)	5.2 (1.0)	5.4 (1.2)	5.4 (1.1)	5.4 (1.0)	5.4 (1.0)
HDL cholesterol (mmol/L)	1.6 (0.4)	1.6 (0.4)	1.5 (0.5)	1.6 (0.4)	1.6 (0.4)	1.6 (0.4)
LDL cholesterol (mmol/L)	3.2 (1.0)	3.0 (1.0)	3.2 (1.1)	3.2 (1.0)	3.3 (0.9)	3.3 (0.9)
Urine albumin-creatinine ratio (mg/g)	25.9 (132.8)	36.4 (105.9)	47.9 (275.1)	19.6 (48.2)	19.4 (67.7)	16.4 (36.3)
vo2max	26.6 (7.8)	24.8 (7.5)	24.8 (7.5)	26.1 (6.8)	27.0 (8.0)	28.7 (8.7)
rest_hr	57.3 (7.3)	67.8 (5.7)	63.3 (5.0)	58.4 (4.5)	55.0 (4.2)	49.8 (4.9)
med_any_anti_hypertensive	753 (47%)	88 (61%)	149 (48%)	216 (47%)	147 (43%)	153 (43%)

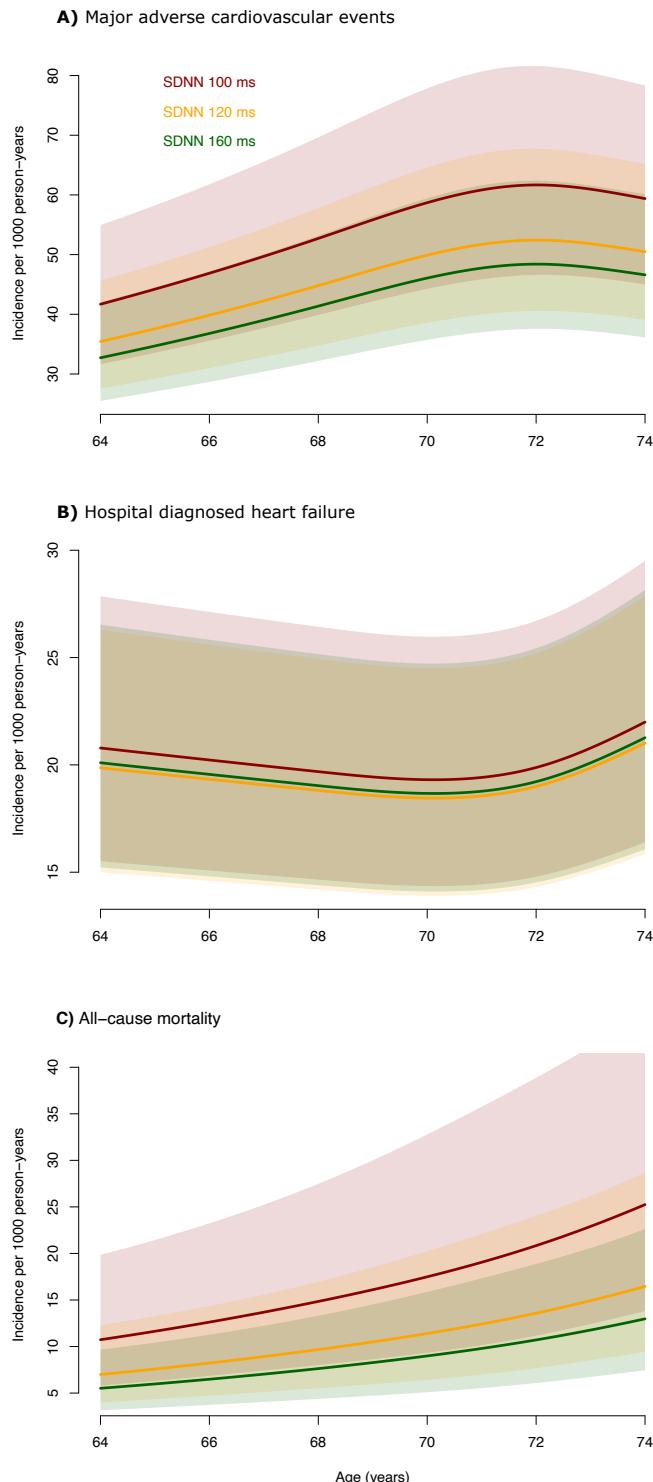
Categorical variables: n (%) Continuous variables: Mean (SD)

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5.2.2 Multiday HRV and MACE, heart failure, and all-cause mortality.

The mean multiday SDNN was 139.0 (32.3) ms, and the mean heart rate was 73.5 (9.1) bpm⁸⁸. In the fully adjusted model, SDNN per SD was associated with a lower incidence rate ratio (IRR) for MACE 0.82 (CI: 0.69; 0.97), heart failure 0.76 (CI: 0.58; 0.99), and mortality rate ratio of 0.79 (CI: 0.66; 0.94)⁸⁸. In model with pre-adjustment for resting heart rate, the proportion of the association explained between HRV and MACE, HF, and all-cause mortality was 14%, 25%, and 19%, respectively⁸⁸. When knots were included in the model, the risk higher as SDNN dropped below approximately 120–110 ms (around the 20th percentile), suggesting a potential threshold for elevated risk⁸⁸. Therefore, incidence rate (IR) was calculated at SDNN levels of 100 ms, 120 ms, and 160 ms, respectively, and plotted these as a function of age.

5.2 Study II



Multiday SDNN levels (100 ms, 120 ms, 160 ms) by age-specific incidence rates for A) major adverse cardiovascular events, B) heart failure hospitalisation, and C) all-cause mortality. Model adjusted for age, sex, education, alcohol consumption, smoking behavior, physical activity, body mass index, total cholesterol, and Hba1c. Figure was based on data in Study II⁸⁸.

Figure 5.3: Multiday SDNN and mean HR association with major adverse cardiovascular events, heart failure, and all-cause mortality

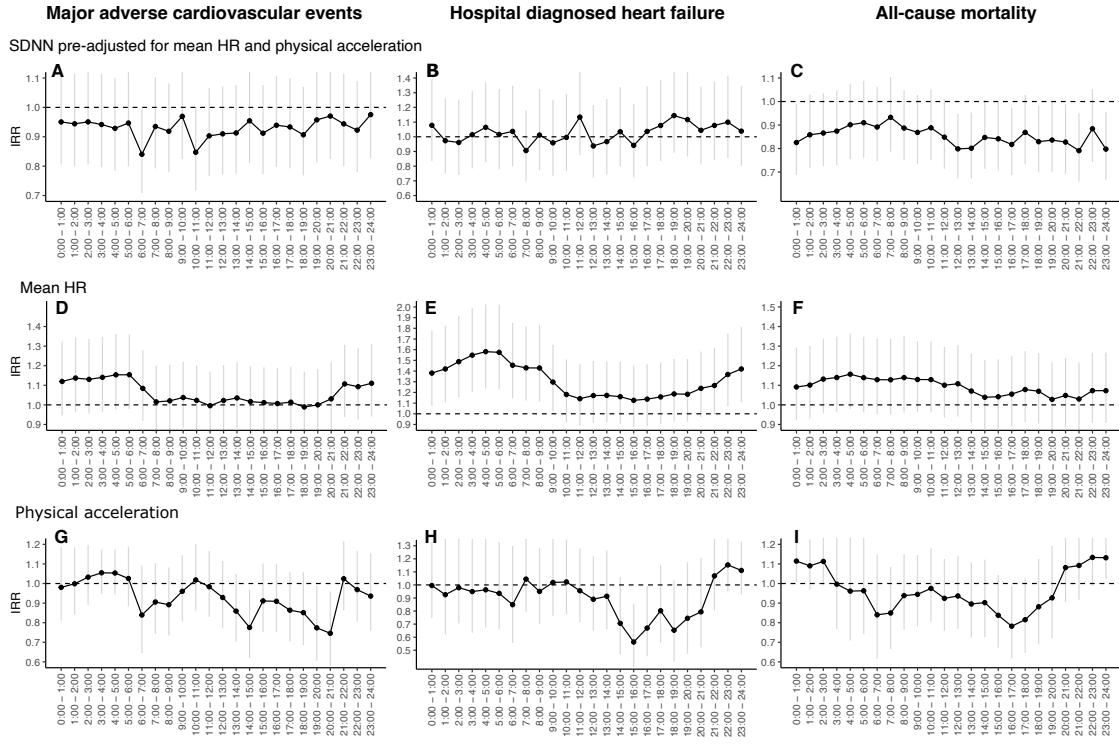
At age 65, the IR per 1000 person-years for MACE was 44.2 (CI: 33.5; 58.3) at SDNN = 100 ms, which was higher than the rates observed at SDNN = 120 ms (IR: 37.6 [CI: 29.2; 48.3]) and SDNN = 160 ms (IR: 34.7 [CI: 27.0; 44.5]) (Figure ?? A). The IR became higher with age, reaching its peak at age 72. For heart failure at age 65, the IR was 20.5 (CI: 15.3; 27.5) at SDNN = 100 ms, slightly higher than at SDNN = 120 ms (IR: 19.6 [CI: 14.8; 25.9]) and SDNN = 160 ms (IR: 19.8 [CI: 15.0; 26.2]) (Figure ?? B). The IR remained stable until age 70, after which it became higher. For all-cause mortality at age 65, the IR was 11.6 (CI: 6.3; 21.4) at SDNN = 100 ms, higher than at SDNN = 120 ms (IR: 7.6 [CI: 4.3; 13.3]) and SDNN = 160 ms (IR: 6.0 [CI: 3.4; 10.4]) (Figure ?? C). The IR for all-cause mortality became higher with age.

5.2.3 Hourly HRV and MACE, heart failure, and all-cause mortality.

From the hourly recordings, I observed a clear periodicity in SDNN, heart rate, sleep patterns, and physical acceleration. Mean (SD) SDNN increased from 5–6 AM (70.2 [28.8] ms), peaking at 8–9 AM (92.1 [29.0] ms), followed by a gradual decline, reaching its lowest point around 2 AM the next day (64.1 [28.1] ms)⁸⁸. A similar circadian pattern was observed in heart rate, although its peak occurred two hours later, starting at 9 AM (76.7 [10.9] bpm)⁸⁸. After peaking, heart rate remained stable throughout the afternoon before gradually decreasing⁸⁸.

In Figure ??, I observe hourly SDNN (preadjusted for heart rate and physical acceleration), heart rate, and physical acceleration association. Models was adjusted for age, sex, education, alcohol consumption, smoking behavior, BMI, total cholesterol, and Hba1c. The morning response of SDNN was most indicative of MACE, with the strongest association observed from 6–7 AM (IRR: 0.84; 95% CI: 0.71 to 1.00 per SD higher SDNN) (see Figure ?? A)⁸⁸. Heart rate between 12 AM and 6 AM showed a small trend toward higher risk of MACE (IRR range: 1.11 to 1.15 per SD higher heart rate), although none of the confidence intervals exceeded one (see Figure ?? D)⁸⁸. Across all hours, there was a plausible association between SDNN and heart failure. However, this association disappeared after adjusting for physical acceleration and heart rate (see Figure ?? B)⁸⁸. In contrast, heart rate between 10 PM and 9 AM was associated with heart failure (IRR range: 1.37 to 1.58 per SD higher heart rate) (see Figure ?? E). SDNN was consistently associated with all-cause mortality across all hours, with a stronger inverse association observed between 12 PM and 1 AM (IRR range: 0.79 to 0.88 per SD higher SDNN) (see Figure ?? C)⁸⁸. No clear trends of association were observed between heart rate and all-cause mortality⁸⁸.

5.3 Study III



SDNN preadjusted for concurrent physical acceleration and heart rate, as well as mean heart rate (HR) and physical acceleration, were measured hourly from 00:00 to 24:00. The IRR for MACE, heart failure hospitalization, and all-cause mortality are shown by hourly associations of: (A–C) preadjusted SDNN, (D–F) mean HR, and (G–I) physical acceleration. Models were adjusted for age, sex, education, alcohol consumption, smoking behavior, body mass index, total cholesterol, and HbA1c. Figure adapted from Appendix Study II⁸⁸

Figure 5.4: **Diurnal heart rate variability and heart rate association with major adverse cardiovascular events, heart failure, and all-cause mortality risk**

5.3 Study III

5.3.1 Descriptive

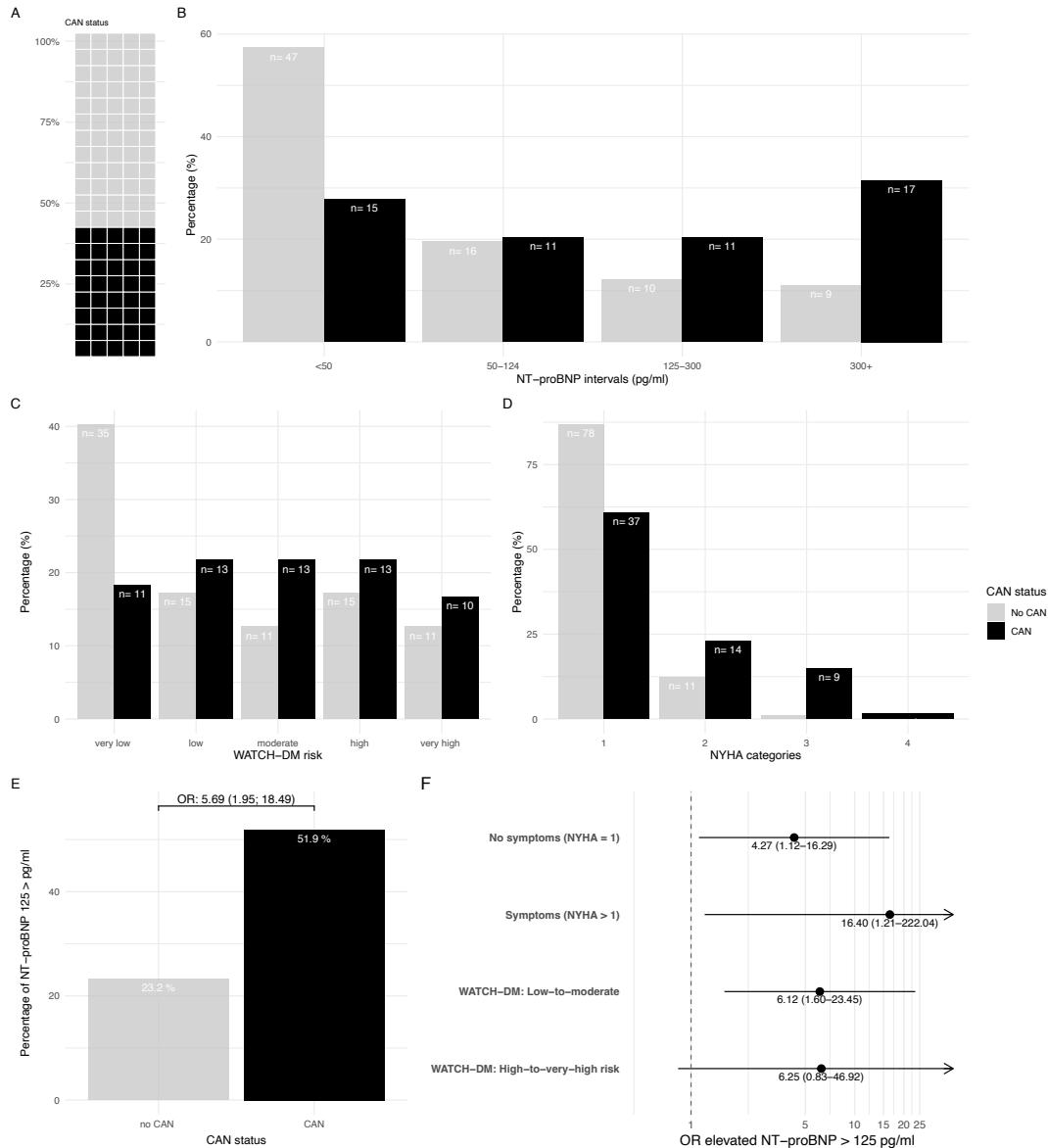
In study III, 179 participants with type 2 had measures of NT-proBNP and performed the CART test. CAN was present in 30% ($n = 54$) of participants (36% among those with valid CAN measurements (Figure ?? A)). Meanwhile, 24% ($n = 43$) were unable

to complete the CART assessment adequately, primarily due to irregular heart rhythms ($n = 8$) or insufficient air pressure during the Valsalva manoeuvre ($n = 21$). Compare to those without CAN, the participants with CAN were more women (41 % vs 33 %), were more sedentary (45% vs 36%), had a higher proportion with prior major CVD (41% vs 20%) and declined eGFR (< 60) (36% vs 22%), higher levels of triglyceride (median 2.05 mmol/L vs 1.95 mmol/ L), were slightly older (median 62 years vs 61 years), had longer duration of T2D (median 19 years vs 15 years), and higher use SGTL2-inhibitors (65% vs 60%) but lower use of GLP-1 RA (63% vs 70%). No other difference in clinical characteristic was observed.

5.3.2 CAN and indicators of heart failure

A greater proportion of individuals with CAN exhibited elevated NT-proBNP levels (>125 pg/ml) (51.9%, $n=52/78$) compared to those without CAN (23.2%, $n=26/112$)(Figure ?? E)⁸⁹. The fully adjusted odds ratio (OR) for elevated NT-proBNP in individuals with CAN was 5.69 (95% CI: 1.95; 18.49) relative to those without CAN⁸⁹. Among the cardiovascular autonomic reflex tests (CART), the Valsalva maneuver demonstrated the strongest association with NT-proBNP (OR 9.00, 95% CI: 2.88; 33.09; $n=51/75$), followed by deep breathing (OR 3.30, 95% CI: 1.17; 9.77; $n=33/133$) and orthostatic hypertension (OR 4.04, 95% CI: 1.27; 13.77; $n=24/146$)⁸⁹. No significant association was identified for the lying-to-standing test (OR 0.80, 95% CI: 0.32; 1.97; $n=54/108$)⁸⁹. After imputing missing CART data, the OR for CAN in relation to elevated NT-proBNP declined to 2.94 (95% CI: 1.37; 6.56). Sensitivity analyses, which excluded participants using beta-blockers or those with a history of CVD, resulted in a smaller sample size and wider confidence intervals, though the overall association remained unchanged⁸⁹. CAN was associated with elevated NT-proBNP in individuals both without (NYHA I; OR = 4.3, 95% CI: 1.1; 16.3) and with heart failure symptoms (NYHA II; OR = 16.4, 95% CI: 1.2; 222.0), though the interaction was not significant ($p = 0.4$)⁸⁹. Similar associations were seen across WATCH-DM risk groups: very-low-to-moderate (OR = 6.1, 95% CI: 1.6; 23.5) and high-to-very-high (OR = 6.3, 95% CI: 0.83; 46.9)⁸⁹. Participants with CAN had 1.7 (95% CI: 0.3 to 3.0) point higher WATCH-DM risk score compared to those without CAN⁸⁹. The OR of presenting with NYHA class II or higher was 5.51 (95% CI: 1.9 to 15.97) in the group with CAN.

5.3 Study III



A: Percentage distribution by CAN status (no CAN, CAN). B: Percentage distribution of NT-proBNP level categories stratified by individuals with and without CAN. C: Percentage distribution of WATCH-DM risk score stratified by individuals with and without CAN. D: Percentage distribution of NYHA classification stratified by individuals with and without CAN. E: Percentage of individuals with $\text{NT-proBNP} > 125 \text{ pg/ml}$ among those with and without CAN and adjusted odds ratio from Model 4. F: Effect modification of the association between CAN and NT-proBNP by symptoms defined by NYHA classification (symptoms: NYHA II vs no symptoms: NYHA I) and risk score defined by WATCH-DM risk (very-low-to-moderate vs high-to-very-high risk). Figure from Appendix Study III⁸⁹.

Figure 5.5: Distribution of NT-proBNP, NYHA Class, and WATCH-DM Score by CAN Status, and association of CAN with Elevated NT-proBNP

6 Discussion

The aim of this dissertation is to understand how cardiovascular autonomic dysfunction and CAN affect the risk of CVD across stages of glucose metabolism. Given the rising prevalence of prediabetes and T2D, and their association with increased risks of CVD and heart failure, there is a pressing need for earlier indicators to help healthcare providers intervene in a timely manner and prevent progression to more advanced stages of cardiovascular complications. One promising approach involves leveraging data from wearable devices and standardized screening tools. Heart rate dynamics and variability across different circumstances may hold promise as accessible indicators for early cardiovascular risk stratification.

This chapter presents a summary of the main findings from this dissertation, interpreted in the context of existing evidence in the field, and discusses their clinical relevance across different levels of healthcare. Moreover, the strengths and limitations of the methods and results will be discussed.

6.1 Summary of findings

In this dissertation, autonomic dysfunction, defined by long-term HRV and standardized CARTs, and its relationship with cardiovascular complications were studied across three different cohorts representing populations at varying levels of prevention and care, including public health, primary care, and secondary care. In The Maastricht Study (Study I), I investigated autonomic dysfunction, measured by 24-hour HRV, and arterial stiffness, measured dynamically along the descending aorta and locally at the carotid site among individuals with NGM, prediabetes, and T2D. Lower HRV was associated with higher aortic and carotid stiffness. This association was evident regardless of glucose metabolism status, and was more pronounced in individuals with prediabetes or T2D. The modifying effect of dysglycemia was confirmed by a statistically significant stronger association across higher HbA1c levels. Z-scores of time- and frequency-domain measures showed the strongest associations, primarily driven by HRV indices reflecting total variation in interbeat intervals (SDNN, SDANN, SDNN index, ULF, VLF, TP).

Study II focused on individuals at higher risk of developing diabetes, using data from the ADDITION-PRO cohort. In study II, lower SDNN, measured over a multiple days, was associated with 18%, 24%, and 21% higher risk per SD for ischemic-related CVD, hospitalization of heart failure, and all-cause mortality, respectively. The risk became higher at SDNN levels below 120 ms, supported by a greater difference in incidence rates between individuals with 100 ms and 120 ms than the difference observed between individuals with 120 ms and 160 ms. Hourly measures suggested a specific time point related to ischemic-related CVD, as lower SDNN recorded between 6:00 and 7:00 AM was associated with MACE. Adjustment using the residuals method for concurrent heart rate and physical movement did not explain the observed association. Hourly SDNN was associated with all-cause MRR, although no specific time point showed an exceptionally strong association. While no association between hourly SDNN and heart failure was observed, higher heart rate during the night hours from 02:00 to 06:00 AM was linked to an higher risk of heart failure hospitalization.

These findings suggest that both long-term HRV measures and hourly HRV responses may serve as indicators of CVD risk. However, a key observation is that long-term HRV was assessed under free-living conditions, which restricts the comparability of results to standardized tests of autonomic function, although it provides insights that are more comparable to what may be found with long-term wearable devices. In the CANCAN Study (Study III), standardized CARTs were used to define CAN and to describe indicators of heart failure, including elevated NT-proBNP, WATCH-DM risk, and NYHA classification, among individuals with and without CAN in a population with T2D. In CANCAN, two out of five had CAN. Compared to individuals without CAN, these individuals more often showed signs of heart failure, including elevated NT-proBNP

6.2 Cardiovascular autonomic dysfunction and its impact on heart disease across glucose metabolism

levels, higher WATCH-DM risk scores, and higher classifications on the NYHA. CAN was associated with elevated NT-proBNP levels and these persisted even among individuals without heart failure symptoms based on NYHA classification, as well as among those categorized as having low to moderate heart failure risk according to the WATCH-DM score.

In summary, various aspects of autonomic dysfunction and cardiovascular complications were investigated in populations with normal glucose metabolism, prediabetes, or T2D. The overall findings showed that autonomic function, assessed through heart rate dynamics of long-term HRV and diurnal HRV or heart rate responses to reflex tests, is associated with an increased risk of CVD and heart failure. This relationship appears to be stronger in more severe stages of dysglycemia. Moreover, among individuals with T2D, the presence of CAN may help identify those at higher risk of heart failure, even in the absence of heart failure symptoms.

6.2 Cardiovascular autonomic dysfunction and its impact on heart disease across glucose metabolism

This dissertation shows that autonomic dysfunction, measured by HRV and CARTs, is associated with CVD risk across the spectrum of glucose metabolism dysregulation. This association is evident with measures of arteriosclerosis, atherosclerotic events, all-cause mortality, and heart failure in individuals at high risk of diabetes, as well as with indicators of heart failure in patients with T2D.

6.2.0.1 Arteriosclerosis

In Study I, autonomic dysfunction, measured by 24-hour HRV, showed to be associated with arterial stiffness, measured both dynamically (cf-PWV) and locally (CD). This suggests that autonomic responses under free-living conditions contribute to the development of arterial stiffness. The majority of studies in the field have shown an association between autonomic dysfunction, as measured by short-term HRV during rest, and arterial stiffness in populations with either type 1 or T2D.⁹⁰ Study I extended this perspective by examining long-term HRV and focusing on a population without diabetes or prediabetes.

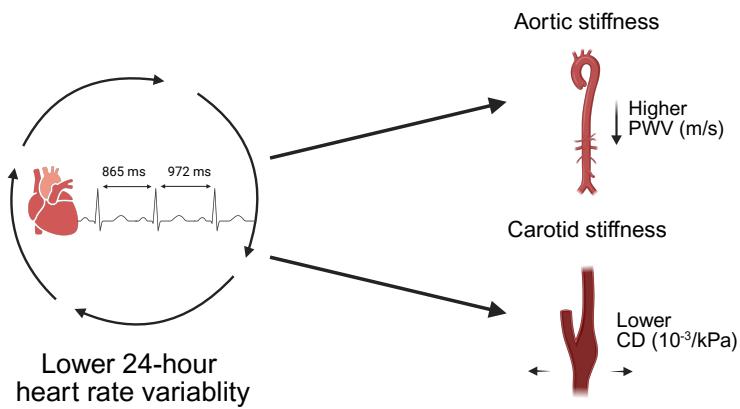


Figure 6.1: Autonomic dysfunction and arterial stiffness. (Source: Author). —.

Arterial stiffness is not only a structural marker of vascular ageing but is also dynamically modulated by local endothelial signals and autonomic nervous system activity. Several studies have demonstrated a link between elevated sympathetic tone and increased arterial stiffness^{[91][92]}. Two possible mechanisms may explain how autonomic dysfunction is related to arterial stiffness. First, autonomic dysfunction may increase the vascular tone of large arteries, thereby impairing arterial elasticity dynamically. This concept is supported by animal studies. In rats, proper autonomic regulation has been shown to be essential for maintaining aortic elasticity. Based on this mechanism, the association between autonomic dysfunction and arterial stiffness might be considered an immediate, and likely transient effect, expected to reverse if autonomic function is restored. Conversely, chronic overstimulation of sympathetic activity can lead to structural remodeling and increased arterial stiffness^[93]. While such findings cannot be directly extrapolated to humans, they suggest plausible biological pathways. Although the initial effects of autonomic dysfunction are dynamic and amenable to change by intervention, they may become progressively less reversible over time^{[93][94]}. Second, the autonomic nervous system regulates heart rate and cardiac contractility. Autonomic dysfunction typically manifests as both reduced HRV and elevated resting heart rate. Arterial shear stress increases as a result of heightened sympathetic activity and parasympathetic withdrawal. A higher resting heart rate may contribute to structurally stiffer arteries by altering blood flow dynamics and by increasing shear stress. Our earlier study using data from the Whitehall II cohort showed that a steeper decrease in short-term (5-minute) HRV over a ten-year period was linked with higher levels of aortic stiffness in the subsequent

6.2 Cardiovascular autonomic dysfunction and its impact on heart disease across glucose metabolism

five years⁹⁵.

The association between 24-hour HRV and arterial stiffness (Study II) was modified by dysglycemia, suggesting dysglycemia may induce CAN that can affect arterial stiffness, even before the onset of T2D^{[96]9798}. Data from the Whitehall II study showed that aortic stiffness increased more steeply with higher HbA1c values among non-diabetic individuals⁹⁹, supporting this notion. In the subpopulation in Study I without diabetes, a modification by HbA1c in both aortic and carotid stiffness was observed. The modifying effect of HbA1c suggests that hyperglycaemia amplifies the consequences of autonomic dysfunction.

6.2.0.2 Atherosclerosis

Study II showed that individuals with a preclinical stage of autonomic dysfunction, measured by multiday HRV, face a higher risk of incident ischemic CVD, heart failure, and all-cause mortality.

Multiday HRV was assessed to capture autonomic activity in real-life settings across several days. Our results are consistent with earlier research linking lower HRV (including measures from 10 seconds to 24 hours) to CVD and mortality [100]⁵. Our findings build on existing evidence by (1) focusing on a population at elevated risk of diabetes, (2) utilizing multiday HRV recordings, and (3) identifying specific periods within the day where HRV patterns were indicative of ischemic-related CVD risk. By using both week-long and hourly data, we identified specific periods that provide a better indication of long-term risk. A strength of using multiday HRV recordings, is to provide more robust insights into individual autonomic patterns by averaging autonomic responses across typical daily conditions. This reduces the influence of random fluctuations caused by factors such as physical activity, emotional states, or sleep on any single day¹⁰¹.

Multiple mechanisms may explain how autonomic dysfunction contributes to the initiation and progression of ischemic events and stroke. First, as discussed in Study I, autonomic dysfunction may promote arteriosclerosis, leading to arterial stiffness through a dynamic and potentially modifiable process. Arterial stiffness impairs vasodilation, increasing hemodynamic stress and the risk of plaque rupture and thrombus formation [102]¹⁰³. In this context, findings from Study I may not entirely distinguish between arterial stiffness and atherosclerosis, as shown by data from the Rotterdam Study¹⁰⁴. As plaques develop, the associated increase in sympathetic nerve density around the arteries could transiently reduce vascular tone which over time reduce arterial elasticity¹⁰⁵. In a smaller study of people with T2D, lower HRV was linked with increased carotid atherosclerosis¹⁰⁶.

6 Discussion

Second, the autonomic nervous system innervates the adventitia layer of blood vessels, where it modulates vascular tone via sympathetic fibres. Although atherosclerotic plaques form in the intima layer, recent *in vivo* studies have demonstrated that increased plaque burden is associated with higher local sympathetic nerve density, likely mediated by neuroinflammatory processes. Notably, reducing sympathetic innervation has been shown to attenuate plaque formation in animal models¹⁰⁷. These findings suggest that autonomic dysfunction may not only reflect but also actively contribute to atherogenesis.

Third, autonomic nervous dysfunction has been shown to interfere with signalling pathways controlling heart rhythm, potentially leading to arrhythmias that disturb cardiac contraction. Earlier studies have shown lower short-term HRV was associated with incident atrial fibrillation (AF), with a higher risk among participants with T2D [¹⁰⁰]¹⁰⁸. This supports the role of autonomic dysfunction in arrhythmogenesis, which increases the risk of myocardial infarction and stroke. Study II did not include AF as an outcome due to limitations in Danish registries, which often do not distinguish between short- and long-term AF, thereby affecting diagnostic validity.

A study of individuals with coronary artery disease showed that stress-induced HRV was associated with myocardial infarction, even more than resting HRV, suggesting that lower parasympathetic modulation of heart rate under stress may play a role in ischemia¹⁰⁹. Our study focused on long-term HRV under free-living conditions, capturing stress-responsive periods such as morning awakening. These recordings likely reflect underlying autonomic dynamics relevant to cardiovascular risk. A Genome-Wide Association Study (GWAS) in the UK biobank of short-term HRV supports this by identifying mechanisms involving G-protein signaling, pacemaker activity, and mitochondrial function as likely mediators of the genetic contribution to HRV. These pathways influence vagal control, cardiac excitability, and energy metabolism¹¹⁰. Although derived from short-term recordings, these genetic associations may reflect autonomic traits that persist across different time scales, and reinforce the notion of a biological basis for inter-individual differences in HRV, preceding and independent of the onset of dysglycemia. A Mendelian randomization study using data from the Rotterdam Study found that genetically predicted HRV was associated with a higher risk of AF¹¹¹. However, this association did not extend to all-cause mortality or cardiovascular death in the UK Biobank cohort, where only phenotypically measured HRV showed a significant relationship with these outcomes¹¹². Interestingly, the genetic determinants of HRV exhibited pleiotropic relationships with several autonomic traits, including resting heart rate, heart rate response during exercise, and post-exercise recovery dynamics¹¹². No GWAS has yet been conducted for long-term HRV. Therefore, it is unclear whether the genetic influences identified for short-term HRV are applicable to long-term HRV. Future GWAS efforts targeting long-term HRV could help establish causal relationships to CVD by

6.2 Cardiovascular autonomic dysfunction and its impact on heart disease across glucose metabolism

leveraging methods such as Mendelian randomization, and advancing our understanding of the genetic architecture underlying autonomic regulation under a full day.

6.2.0.3 Heart failure

The relationship between cardiovascular autonomic dysfunction and heart failure is complex¹¹³. On one hand, autonomic dysfunction contributes to cardiac remodelling and eventual heart failure. On the other hand, it may reflect compensatory mechanisms of the progression of cardiac remodelling and declining cardiac output. Our findings demonstrated a relationship between autonomic dysfunction and heart failure both cross-sectionally in a population with T2D and prospectively in individuals representing different tiers of diabetes risk. However, our data are limited in determining the extent to which this relationship supports one explanation over the other, as we lack baseline and follow-up measures of both heart failure and HRV. Earlier studies have demonstrated that both short-term and long-term HRV are associated with incident heart failure in populations with and without T2D.^{[114][115][116][117]} Beyond examining a population at elevated risk of diabetes using multiday HRV recordings, we expanded previous research by (1) unmasking the role of resting heart rate in the relationship between HRV and heart failure risk, and (2) identifying specific times of day when heart rate patterns signaled higher risk of heart failure.

Several mechanisms may underlie the role of autonomic dysfunction in advancing heart failure. Findings from Study I confirmed the relationship between autonomic dysfunction and arterial stiffness. It is well established that arterial stiffness is linked to cardiac remodelling, as increased cf-PWV leads to an earlier return of the reflected pulse wave to the aorta, which increases cardiac afterload and reduces coronary perfusion pressure¹¹⁸. Therefore, autonomic dysfunction may have an indirect effect on heart failure, potentially mediated by arterial stiffness. However, structured analyses are needed to confirm these pathways. For example, mediation analysis with repeated measurements could be employed to assess the temporal direct and indirect effects of autonomic dysfunction on measures of cardiac remodeling, with arterial stiffness as the mediator.

Study II showed that multiday HRV was associated with incident heart failure, and approximately one-fourth of the risk was explained by resting heart rate. Data from the Rotterdam Study showed that short-term HRV was longitudinally associated with echocardiographic measures reflecting systolic function, suggesting that autonomic dysfunction contributes to cardiac remodelling¹¹⁹. In contrast to MACE outcomes, findings from Study II showed no specific time point in hourly HRV that was associated with heart failure. Instead, it was the overall daily pattern captured by multiday HRV that was linked to heart failure risk. This suggests that the association is not driven by isolated shifts in autonomic activity in response to circadian stressors, but rather by a

consistently impaired autonomic balance under free-living conditions. The effect appears to be driven in part by a failure to show appropriate decreases in heart rate during rest, as individuals with higher hourly heart rates at night had a higher risk of heart failure. In Study III, I observed that individuals with CAN had higher risk of elevated levels of NT-proBNP, a biomarker of myocardial stress and early heart failure. Therefore, CAN is associated with hemodynamic consequences that contribute to both structural and functional cardiac remodeling, which in turn leads to elevated NT-proBNP levels.

We cannot rule out that autonomic dysfunction reflects a compensatory response to progressing heart failure, suggesting potential reverse causation. In addition, it remains unclear to what extent the parasympathetic nervous system can act as a protective mechanism to counterbalance sympathetic dominance, and whether a decline in HRV reflects a breakdown of this balance. The two pathways (autonomic neuropathy and cardiac remodelling) are not mutually exclusive and may interact in a reinforcing cycle. Autonomic dysfunction can lead to increased sympathetic tone and reduced parasympathetic modulation, placing the heart under chronic stress and promoting structural and functional changes²⁴. In turn, cardiac remodelling may impair autonomic regulation, further exacerbating the imbalance. This interplay may create a self-perpetuating loop that accelerates the progression of heart failure. However, this remains beyond the scope of our current data and analysis.

6.3 Clinical implications

The dissertation investigates autonomic dysfunction in populations ranging from normal glucose metabolism to T2D and yields insights relevant for individuals who engage with the healthcare system at different levels. No specific role has yet been defined for autonomic dysfunction in clinical decision-making within healthcare, as current treatment and intervention options specifically targeting autonomic function remain limited. Despite the fact that the results do not point directly to where and how implementation of autonomic dysfunction in clinical practice may make sense, the included studies broadly represent situations relevant to public health, primary care, and secondary care settings. In the following section, the clinical implications of using autonomic dysfunction in the prevention of CVD will be discussed. If long-term HRV or CARTs are to be considered for improving risk stratification, it is important to determine at what stage in the progression of diabetes risk, and at which level of care, autonomic dysfunction becomes meaningful for early detection and intervention.

6.3.1 Public health

A central strategy in preventing CVD is the early identification and multifactorial treatment of individuals at high risk¹²⁰. Public health initiatives support this by promoting healthy lifestyles, facilitating early screening for risk factors, and improving access to essential care and medications. Long-term HRV may enhance these efforts by identifying individuals with elevated cardiovascular risk and by tracking their physiological response to lifestyle changes.

Evidence from Study I showed that lower long-term HRV was associated with increased arterial stiffness, as measured by cf-PWV and CD, even in individuals without T2D. One standard deviation lower HRV corresponded to the effect of 2.7 additional years of ageing on aortic stiffness (cf-PWV) and 1.6 years on carotid stiffness (CD)⁷⁴. These cross-sectional findings suggest that HRV may serve as a marker of early vascular aging and cardiovascular risk. Supporting this, the Whitehall II study demonstrated a longitudinal relationship between short-term HRV and aortic stiffness. Together, these findings highlight the potential of HRV as a indicator of vascular health.

Within the public health setting, individuals with prediabetes represent a particularly vulnerable group at risk for comorbidities¹²¹. They often fall between structured care pathways, sometimes encouraged to reassess their cardiovascular risk at more frequent intervals, other times not offered any additional measures or attention beyond general lifestyle advice. Notably, Studies I and II demonstrated that the associations between long-term HRV and CVD risk were especially pronounced in this population. In those at high risk of diabetes, a one standard deviation (33 ms) lower multiday SDNN was equivalent to 4.5 additional years of aging for ischemic-related CVD and 2.2 to 2.4 years for heart failure⁸⁸. On a population level, lower HRV (SDNN: 100 ms) in individuals with prediabetes was associated with a higher incidence rate of CVD, heart failure, and all-cause mortality compared to individuals with normal-to-higher HRV (SDNN: 120–160 ms). These findings reinforce the role of HRV as an early and sensitive marker of cardiovascular health in populations at cardiometabolic risk.

While these findings highlight HRV's potential, practical implementation faces several challenges. Historically, long-term HRV monitoring has required specialized equipment such as Holter ECG recorders. However, the growing popularity of wearable devices offers a promising alternative. These devices provide a non-invasive, user-friendly way to collect heart rate and HRV data over time¹¹, under free-living conditions like those examined in Study II.

If HRV monitoring proves effective in helping individuals maintain a healthy, age-adjusted HRV range through lifestyle changes and prompts healthcare engagement when HRV deteriorates, it could become a meaningful tool for long-term health tracking. A

cross-sectional study of 8 million individuals found that those who took more steps per day had higher HRV¹³, suggesting that HRV may also reflect behavioral adaptation.

A major public health challenge lies in ensuring equitable access to wearable technology. Individuals from lower socioeconomic backgrounds are less likely to own such devices, raising concerns about health disparities. Despite this, there is encouraging evidence that the general population is receptive to digital health innovations. Many are willing to share health data with public institutions and support the use of AI in disease monitoring^[11]^[122].

Integrating wearable HRV monitoring into public health strategies could represent a transformative step in proactive cardiovascular care. It may support early detection, personalized prevention, and timely referral to primary care when risk levels increase.

6.3.2 Primary care

Cardiovascular risk in primary care is assessed using clinical evaluations and standardized risk prediction tools to identify individuals at elevated risk. Management focuses on lifestyle modification, pharmacological therapy, and regular monitoring to reduce cardiovascular events¹²³. In this context, long-term HRV may offer added value by improving the precision of cardiovascular risk stratification and by serving as a marker to monitor the effectiveness of preventive strategies.

Long-term HRV may improve ranking of individual risk when added to established clinical risk scores. Tools such as SCORE2 and the Framingham Risk Score are widely used in primary care to guide cardiovascular risk assessment^{124,125}. In Study I, models adjusted for conventional CVD risk factors supported the potential added value of 24-hour HRV in relation to arterial stiffness, a surrogate marker of CVD risk. Study II extended this perspective by demonstrating associations between multiday HRV and incident CVD and heart failure. However, these findings are based on associations and do not include formal prediction modeling¹²⁶, and therefore cannot determine whether incorporating long-term HRV or CARTs into existing risk scores improves predictive performance beyond current guidelines. This analysis is limited in ADDITION-PRO, as the cohort doesn't reflect high-risk groups typically identified in primary care, such as those with elevated HbA1c. Similarly, CANCAN is constrained by its small sample size and selection from secondary care. To properly assess predictive value, cohorts should broadly represent individuals with T2D or those at high risk, as identified by current clinical practice. While most biomarkers have shown limited incremental value beyond established predictors (including age, sex, lipid profiles, diabetes status, and blood pressure), some studies suggest that 24-hour HRV may improve risk discrimination for CVD and all-cause mortality in individuals with T2D¹²⁷, and for stroke and heart failure in

6.3 Clinical implications

older adults^{[114]¹²⁸}

However, these studies often lack calibration or validation in large-scale cohorts and have not been integrated with widely used risk scores such as SCORE2 or the Framingham Risk Score.

Long-term HRV may also help classify preclinical autonomic dysfunction, enabling targeted interventions in a subgroup of patients to prevent CVD. The increasing availability of wearable devices capable of capturing long-term HRV data presents a practical opportunity for continuous monitoring in primary care. These devices may facilitate earlier detection of autonomic dysfunction and support more personalized approaches to cardiovascular risk management. However, the clinical utility of stratifying patients based on preclinical autonomic dysfunction remains uncertain. These considerations are only actionable if interventions in this subgroup can be shown to reduce cardiovascular risk. Emerging evidence suggests that both pharmacological and lifestyle interventions can improve HRV in the short term^{129,130}. For example, high-intensity interval training has been shown to improve autonomic function in obese individuals with and without T2D¹³¹. Similarly, lifestyle changes in individuals with prediabetes have been associated with improvements in short-term HRV, which may partly explain a reduction in diabetes risk independently of weight loss¹³². Nevertheless, it remains unclear whether these effects on HRV are sustainable over time and whether they translate into long-term cardiovascular protection. In many cases, improvements in autonomic function may be mediated indirectly through changes in cardiometabolic markers such as glucose levels, lipid profiles, body weight, maximal oxygen uptake, and blood pressure.

Despite these uncertainties, monitoring autonomic function through long-term HRV may offer a valuable tool for assessing cardiovascular risk and tracking the impact of preventive strategies. In Denmark, prediabetes, defined by HbA1c, is present in 7.1% of adults¹³³. One in five of these individuals develops T2D within five years¹³³, while others either remain in the prediabetic stage or return to normoglycemia. Despite their higher risk of CVD and heart failure¹³⁴, individuals with prediabetes are not captured by existing preventive strategies. This underscores the need for early and precise risk assessment¹⁰. Given that the cardiovascular consequences of autonomic dysfunction appear to be more pronounced in individuals with prediabetes compared to those with normoglycemia, HRV has the potential to help identify those at elevated CVD risk within this group. However, evidence demonstrating improved risk prediction and sustained effects leading to better cardiovascular outcomes is needed to establish its relevance for integration into primary care.

6.3.3 Secondary care

In secondary care, endocrinologists assess cardiovascular and heart failure risk by integrating advanced diagnostics, biomarker analysis, and imaging to detect early heart fail-

ure, guided by symptoms and risk profiles. The treatment of patients with T2D is guided by evidence-based therapies and multidisciplinary collaboration. The ADA/EASD 2022 consensus on Management of Hyperglycemia in T2D emphasizes that early detection of heart failure in individuals with T2D is crucial, as it enables timely initiation of therapies such as SGLT2 inhibitors, which have demonstrated significant benefits in reducing heart failure-related outcomes⁷⁰. A major challenge in diabetes care is detecting heart failure before symptoms appear, as patients with symptomatic heart failure face a higher risk of mortality and more frequent hospitalizations⁴. The AHA, ACC, and HFSA 2022 guidelines recommend identifying individuals at risk of heart failure based on factors such as diabetes, poor glycaemic control, uncontrolled hypertension, hyperlipidaemia, elevated BMI, albuminuria, renal dysfunction, and a history of CVD⁵⁶. Still, there is a need to identify optimal approaches for recognizing and diagnosing heart failure in clinical care, as broad echocardiographic screening in T2D is time-consuming and costly⁴.

Study III demonstrated that CAN may help identify individuals at higher risk of heart failure, beyond what is captured by symptoms or existing risk scores. Our findings support considering CAN as a relevant risk factor for heart failure and suggest it may have value in future risk stratification strategies in T2D. A clinical advantage of using CARTs is that they are standardized tests performed under controlled conditions. CARTs have proven to be reliable and reproducible, with reference values established in large population studies⁶⁸. Beyond these findings and the established evidence of increased heart failure risk, CAN also identifies individuals at high risk for overall CVD, kidney disease, and early mortality in the T2D population^{[61][62]}. In Study III, I observed that two out of five participants had CAN, highlighting it as a complication with considerable prevalence. Therefore, detecting CAN may uncover an often-overlooked condition that is common in individuals with T2D.

Clinical stratification of care includes two key considerations: (1) CAN should be further evaluated for associated cardiovascular complications, such as heart failure; and (2) cardiopreventive strategies should be initiated earlier in this subgroup.

First, patients with CAN may benefit from further cardiovascular assessment, including the use of sensitive biomarkers or echocardiography. NT-proBNP is a strong predictor of heart failure and a validated biomarker for ruling out the condition (ref.). However, its specificity varies across heart failure phenotypes, being less specific for detecting HFpEF compared to HFrEF. Therefore, additional evaluation using echocardiography may be warranted. Beyond classifying heart failure phenotypes, echocardiography identifies preclinical stages of heart failure through the detection of functional or structural cardiac abnormalities. Including CAN in structured assessments of heart failure could help clarify to which extent CAN overlaps with cardiac abnormalities. Determining the diagnostic and prognostic value of CAN, particularly its sensitivity and specificity in detecting HFrEF and HFpEF, requires further investigation.

6.4 Strengths and limitations

Second, the presence of CAN may justify earlier initiation of protective therapies. SGLT2 inhibitors are recommended as second-line treatment in T2D and have demonstrated benefits in reducing the risk of heart failure, CVD, and kidney function decline, complications commonly associated with CAN. Current guidelines recommend initiating these therapies based on a history of CVD, heart failure, or the presence of conventional high-risk cardiovascular factors. However, the specific impact of SGLT2 inhibitors on the progression of cardiorenal outcomes in patients with CAN remains to be fully understood. Furthermore, while antihypertensive treatment is a cornerstone of cardiovascular risk management, whether specific classes of antihypertensive agents offer protective effects in patients with CAN remains to be explored.

The direct clinical implications of our findings in Study III are limited. The generalizability of our results is restricted, as our study population consisted of patients with T2D receiving secondary care. Two out of five patients with CAN showed to have a history of CVD—a group already at higher risk of heart failure due to their prior diagnosis. This overlap may influence the interpretation of CAN as an independent risk factor. Therefore, these findings need to be validated in a broader population with T2D, including individuals without a history of CVD. Doing so would allow for greater generalizability of our results to the broader T2D population, particularly those visiting primary care.

6.4 Strengths and limitations

6.4.1 Study design

Cross-sectional design

Studies I and III are based on cross-sectional data, with exposure and outcome measured within a three-month period. The main limitation of this design is that it does not allow us to determine whether the exposure led to the outcome or vice versa. As a result, we cannot establish temporality or confirm whether changes in the outcome were caused by the exposure. Based on prior evidence, the direction of the associations in Study I was inferred using physiological knowledge and findings from epidemiological and *in vivo* studies⁹⁵.

Study III focused on the clinical diagnosis of CAN and the presence of heart failure. The research question was oriented toward the clinical utility of CAN in identifying patients with T2D who may be progressing early toward heart failure. Whether cardiac function progressively worsens due to the underlying mechanisms of CAN remains to be fully established.

Longitudinal design

A major strength of Study II is its longitudinal design, where HRV was measured at baseline and outcomes were captured prospectively through national registries. This temporal structure ensures that the exposure (HRV) preceded the outcome, reducing the risk of reverse causation. The prospective design allows for stronger inference of directionality than cross-sectional studies. Furthermore, the use of high-quality registry data ensures complete outcome ascertainment and minimizes loss to follow-up bias.

Causality cannot be ascertained from the findings in Study I and Study II, and more causally focused methods are needed. Mendelian randomization, which uses genetic instruments for exposure, could help address this question. Additionally, structured mediation analysis involving modifications such as medication or lifestyle changes could clarify whether improving HRV or CART reduces cardiovascular risk, using data from intervention studies.

6.4.2 Internal validity

In this project, I aimed to assess cardiovascular autonomic function both in free-living conditions and in response to standardized test procedures during clinical visits. Additionally, I used dynamic measurements to evaluate arterial stiffness both locally and by velocity, and biomarker assessments to determine the presence of heart failure. In this section, I discuss the validity of 24-hour, multiday, and hourly HRV measurements, as well as the standardized tests of CAN. I also address the validity of the included outcomes and discuss the strengths and limitations of using MACE as a time-to-event outcome.

6.4.2.1 Long-term HRV (>24 hours) as measurement for autonomic function

A main consideration in HRV analysis is the reliability of raw inter-beat interval data from ECG recordings. To ensure accurate various HRV measures, the intervals must be captured in a continuous and correctly sequenced manner. Frequency-domain analyses depend on the integrity of the inter-beat interval sequence, while some time-domain measures, such as RMSSD and pNN50, specifically quantify the variability in the differences between successive intervals.

In Study I, data from a 12-lead Holter system was used, which is considered the gold standard for long-term ECG recordings. With detailed and sequential inter-beat intervals, all HRV metrics were calculated.

In Study II, data from the Actiheart device was used for HRV. The device was configured to record continuously over an 8-day period. It captured 30-second epochs of mean heart rate intervals, along with upper and lower prediction intervals. From each

6.4 Strengths and limitations

epoch, I generated a distribution of inter-beat intervals. An algorithm was applied to estimate HRV from these distributions, and its validation showed strong agreement with established metrics, including SDNN, SDANN, and the SDNN index [6]⁸³. However, a limitation of this dataset is that it did not allow for the calculation of frequency-domain measures or specific time-domain metrics such as RMSSD or pNN50.

In the context of this study, which focuses on long-term HRV in free-living conditions, it is important to acknowledge that the autonomic nervous function we aim to assess may also be influenced by behavioral factors such as physical activity, sleep, meal timing, emotions, smoking, caffeine intake, alcohol consumption, medication use, and prior cardiovascular complications. These factors can potentially mask or mimic underlying physiological dysfunction during recordings, but they can also elicit the HRV responses we are interested in. Therefore, lower long-term HRV cannot be interpreted solely as a marker of autonomic function. HRV is also influenced by lifestyle patterns over time, making it sensitive not only to day-to-day behaviors but also to long-term habits that affect autonomic balance.

In Studies I and II, I accounted for habitual physical activity, and in Study II, I also adjusted hourly HRV for physical movement during recordings to test the influence of concurrent activity. However, further studies are needed to understand how lifestyle patterns affect long-term HRV recordings on subsequent days, in order to separate direct behavioural from physiological components. In both studies, I excluded participants with prior CVD to preserve the etiological order between autonomic dysfunction and cardiovascular outcomes.

Anti-hypertensive medications, especially beta-blockers, are known to increase HRV in randomized controlled trials¹³⁵. However, in cohort studies, participants using anti-hypertensives generally show lower HRV, likely reflecting a higher burden of cardiovascular complications [ref]. Because beta-blockers target the autonomic nervous system, they may introduce bias in HRV measurements by interfering with the function. In sensitivity analyses in Studies I and III, excluding participants on anti-hypertensive treatment did not materially change the estimates. Therefore, these participants were kept and adjusted for medication use in the full models.

Beyond the behavioral and pharmacological contribution to HRV, we cannot physiologically distinguish whether autonomic dysfunction is primarily driven by increased sympathetic activity or reduced parasympathetic tone. Much of the current evidence on autonomic contributions to HRV originates from studies involving experimental manipulation of the autonomic nervous system, such as physiological tests (e.g., tilt response, deep breathing, stress response) or pharmacological interventions. Therefore, it remains uncertain whether the mechanisms linking HRV indices to cardiovascular complications are predominantly due to sympathetic overactivity or parasympathetic withdrawal.

HRV levels are influenced by heart rate, as lower resting heart rate allows for greater variability. In Study I, I chose not to adjust for heart rate in our models, as this could introduce multicollinearity. Additionally, elevated heart rate is driven by higher sympathetic activity and may act as a mediator in the pathway leading to arterial stiffness. Our use of full-day recordings captures HRV during both rest and activity, providing a robust representation of autonomic function over a typical day. In contrast, heart rate correction may be more relevant for short-term HRV recordings, where standardized conditions can be affected by random influences such as time of day, smoking, or caffeine intake. These factors would have been relevant in Study III had I included HRV measures. In Study II, I used the residuals method to pre-adjust HRV measures for resting heart rate, which accounted for part of the observed associations, particularly with heart failure and all-cause mortality, and to a lesser extent with ischemic-related CVD events. Similar trends were observed for hourly associations, where heart rate pre-adjustment had had comparable effects on the outcomes.

The three studies demonstrate approaches to identifying CVD risk: (1) selecting appropriate HRV indices, (2) segmenting time intervals, and (3) assessing HRV under defined conditions. Our findings reveal varying associations across HRV indices, with RMSSD and HF showing weaker associations. However, previous research has shown that these indices can be informative when analyzed in 5-minute segments^{129,136}. Additionally, SDNN exhibited varying associations with CVD risk depending on the time of day. We also observed that, in CARTs, the Valsalva maneuver and deep breathing test were more indicative of heart failure. These insights highlight the need for methodological rigor in HRV research, particularly in aligning index selection and time segmentation with specific research objectives and clinical contexts.

6.4.2.2 Cardiovascular autonomic reflex test

CART provides a practical approach for screening for autonomic dysfunction and has been shown to be a reliable method¹³⁷. Although certain indices from CARTs may be influenced by factors such as time of day or recent physical activity, these effects are generally minimal. Furthermore, no impact of caffeine intake has been observed on the reference age-based formula⁶⁸. A limitation of the CARTs in this study was the high prevalence of participants who were unable to complete the full battery of tests, primarily due to missing data from the Valsalva manoeuvre.

6.4.2.3 Measures of cardiovascular risk

In study I, arterial stiffness measures, including pulse wave velocity and carotid artery distensibility, are influenced by mean arterial pressure (MAP), which may confound the

6.4 Strengths and limitations

assessment of vascular stiffness. In Study I, we adjusted for MAP, which attenuated the observed associations. However, the associations remained statistically significant.

In Study II, outcomes were based on CVD events, heart failure, and causes of death from Danish national registries. Potential misclassification and underreporting, especially of heart failure, may have led to underestimation of associations¹³⁸.

In Study III, NT-proBNP was used as a primary indicator of heart failure. While NT-proBNP is a validated biomarker for early-stage heart failure and useful for ruling out the condition, its specificity varies by HF phenotype⁵⁶. Thus, we cannot determine HFpEF or HFrEF. Its diagnostic accuracy is influenced by factors such as AF, obesity, and kidney function⁵⁶. Individuals with AF were excluded by design. Analysis was adjusted for BMI, which did not affect the association between CAN and elevated NT-proBNP. After adjusting for eGFR, the association became stronger, suggesting that reduced kidney function may have masked the true link between CAN and heart failure risk.

6.4.3 External validity

6.4.3.1 Selection bias

The Maastricht Study

The target population in Study I was intended to represent individuals at different stages of glucose metabolism. However, our analysis may be affected by selection bias in the representation of individuals with T2D. The Maastricht Study recruited participants who were able and willing to attend multiple research visits and receive personal health feedback, which likely attracted health-conscious individuals with higher education levels. As a result, participants with T2D were relatively healthy, with a median disease duration of three years and a low prevalence of complications. Those who completed both long-term ECG and arterial stiffness assessments may represent an even healthier subgroup. This selection bias may limit the generalizability of the findings to the broader T2D population and could explain why the effect modification did not differ step-wise from that observed in individuals with prediabetes.

ADDITION-PRO

The target population in Study II was intended to represent individuals at high risk of developing T2D. Participants were recruited through a stepwise screening procedure. Initially, individuals were selected based on a risk score derived from a self-administered questionnaire sent by mail. Those with high scores were invited for further testing using HbA1c or random glucose measurements.

This recruitment strategy involved selection by design, as it defined the source population based on specific risk criteria. The questionnaire prioritized risk factors such as older age and hypertension, leading to overrepresentation of these groups¹³⁹. Prediabetes was identified only after biochemical testing, while the risk score was primarily designed to detect undiagnosed T2D. Although this selection process was intentional and aligned with the ADDITION-PRO objectives, it may limit the generalizability of the findings to the broader population at risk for T2D.

In addition, selection bias may have occurred due to differential participation in the ADDITION screening program. Healthier individuals were more likely to participate, both by completing the risk questionnaire and by attending follow-up testing¹⁴⁰. As a result, the baseline risk for CVD in ADDITION-PRO participants may have been lower compared to the target population.

CANCAN

The target population in Study III was intended to represent individuals with type 2 diabetes treated in outpatient clinics. In Denmark, patients with type 2 diabetes are referred to diabetes specialists at outpatient clinics when their general practitioner is unable to stabilize their condition. A strength of the CANCAN sampling strategy is that patients were already attending endocrinology consultations, and the study examination required only additional time during their visit, without the need for extra transportation or appointments. Assessing selection bias in this study is challenging, as inclusion depended on referral practices by general practitioners¹⁴¹. These practices may vary individually, with differing thresholds for referring patients to specialized care based on clinical judgment and patient characteristics.

6.4.3.2 Generalisability

The generalisability of our findings is considered in the context of the targeted recruitment strategies used in each study, which aimed to include individuals across a spectrum of diabetes risk, from NGM to established type 2 diabetes. As a result, the findings are most applicable to populations with similar clinical profiles and healthcare settings.

Studies I-III include individuals at high risk of diabetes and those with T2D. Therefore, the associations between cardiovascular autonomic dysfunction and cardiovascular outcomes or surrogate biomarkers are relevant to individuals with some degree of diabetes risk and progressed T2D. Study I suggests that the link between autonomic dysfunction and cardiovascular risk, as measured by arterial stiffness, is also present in individuals with NGM, though to a lesser extent. This finding, supported by replication in the Whitehall II cohort⁹⁵, indicates that the observed relationship may extend beyond high-risk groups and into the general population. In study III, participants represent a

6.4 Strengths and limitations

higher-risk diabetes group among Danish diabetes patients, while more stable patients remain under general practitioner care. Consequently, the prevalence of heart failure indicators and CAN is likely higher in this selected group, than patients managed in primary care, and thus limits extending our finding to broader T2D populations.

By design, younger individuals with prediabetes or young-adult-onset type 2 diabetes are underrepresented in our studies. This group may be overlooked in current research and warrants further attention in future studies^{133,142}. The applicability of our findings to other countries may be influenced by differences in demographic composition, risk factor distributions, healthcare systems, and stages of economic development. These factors can affect both the prevalence of diabetes and cardiovascular disease and the nature of their associations. While our study populations were primarily of Nordic and Western European descent, differences in ethnic composition are only one of several factors that may influence external validity. These regions also share relatively well-organized, publicly funded healthcare systems, which may differ substantially from those in other parts of the world and further affect the applicability of our findings.

7 Perspective

This dissertation has investigated autonomic function impact on cardiovascular complications across different stages of glucose metabolism. Based on our findings and conclusions, we propose further perspectives to define its role in research and healthcare from three aspects: (1) continuous non-invasive health monitoring, (2) risk stratification, and (3) identification as a causal and modifiable marker.

7.1 Continuous monitoring of cardiovascular health

Understanding when and how physiological signals reflect elevated CVD risk is essential for developing early and effective prevention strategies. Incorporating HRV into digital health solutions could support personalized feedback mechanisms, enabling timely lifestyle or therapeutic interventions and contributing to more adaptive and preventive healthcare strategies. Digital CVD risk calculators can help optimize the timing of follow-up assessments or the initiation of treatment. In type 1 diabetes, for example, such tools are used to guide decisions on starting lipid-lowering therapy. Similarly, recent analyses at Steno Diabetes Center Copenhagen have shown that not all patients require annual retinopathy screening. Instead, prediction models using clinical variables can determine optimal re-screening intervals. Wearable devices enable comprehensive data collection on behavioral (e.g., sleep and physical activity) and physiological (e.g., heart rate, ECG, temperature) parameters¹⁴³. These devices offer a broader and more feasible approach to long-term heart rate monitoring. Despite growing interest in wearable-based monitoring, the integration of HRV into routine cardiometabolic risk assessment remains limited.

Two key aspects highlight the potential applications of monitoring: (1) identification of risk and (2) assessment of response to intervention.

Identification of risk

Lower long-term HRV is a risk factor for CVD, associated with arterial stiffness and clinical endpoints. Our findings indicate that specific HRV and heart rate patterns under free-living conditions may enhance early risk detection, independent of concurrent physical activity. For improved risk assessment, future predictive models should move beyond adjusting for physical activity as a confounder and instead integrate multiple physiological signals, such as HRV responses to sleep and activity patterns, to better capture dynamic health states. Machine learning offers powerful tools to analyze complex raw time-series data, including interbeat intervals and accelerometer signals, potentially improving risk prediction beyond traditional HRV summary metrics. However, the limited interpretability of these models remains a key barrier to clinical adoption.

Assessment of response to intervention

HRV represents a potential target for intervention, as low HRV may reflect adverse lifestyle patterns. Behaviors such as disrupted sleep, physical inactivity, and irregular meal timing can influence circadian fluctuations in HRV (ref. sleep, activity)¹²⁹. Pharmacological interventions also impact HRV: beta-blockers have been shown to increase HRV, while GLP-1 receptor agonists may reduce it [¹³⁵]¹⁴⁴.

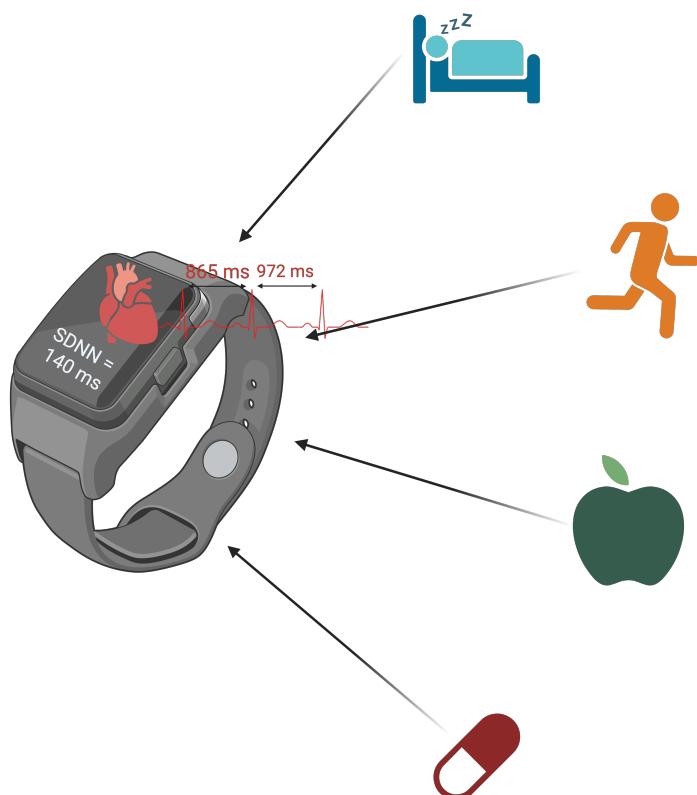


Figure 7.1: HRV feedback in response to lifestyle and treatment interventions. (Source: Author)

Future research can leverage wearable devices to monitor the effectiveness of behavioral and pharmacological interventions on HRV at the individual level. This approach may support precision real-time monitoring to identify lifestyle patterns or treatments that promote cardiovascular health through HRV modulation or uncover potential side effects⁷³.

However, standardization and transparency across wearable device brands remain a chal-

lenge for both research and clinical use. While smartwatches offer convenient heart rate monitoring, their accuracy varies due to reliance on photoplethysmography, which can be affected by motion and other external factors, especially during physical activity [145] [146]. Despite these limitations, ongoing improvements in sensor technology and algorithm calibration are likely to enhance the reliability of wearable-derived HRV and heart rate data. Open data formats are important to ensure that detailed data (e.g. interbeat intervals) from various devices can be used consistently in health prediction algorithms, rather than relying only on summarized outputs.

7.2 Risk-stratification

The distinct roles of long-term HRV and CART in cardiovascular risk stratification remain to be fully established. From a wearable technology perspective, long-term HRV offers two promising avenues that warrant further investigation:

1. Non-invasive risk identification: HRV measured via wearable devices may help identify individuals at elevated cardiovascular risk without the need for invasive measures such as blood pressure readings or blood samples.
2. Enhancement of existing risk scores: HRV may improve the predictive accuracy of established cardiovascular risk models, such as SCORE2 or the Framingham Risk Score.

Both applications require further research to determine their clinical utility and integration into routine risk assessment.

A key limitation of long-term HRV measurement is the lack of standardization, as data collected under free-living conditions may be influenced by daily behaviors, potentially affecting risk classification. This highlights the need for standardized protocols. In contrast, CART is a reliable, non-invasive method that typically takes around 10 minutes to perform. A standardized and validated diagnosis of CAN using CART may help identify individuals with T2D who are at elevated risk of complications. However, the extent to which CAN diagnosis predicts heart failure risk and applies to broader populations with T2D or prediabetes remains to be clarified.

Our findings suggest that long-term HRV and CAN may serve as useful markers for identifying individuals at elevated metabolic risk who could benefit from targeted preventive strategies. Future research should explore whether identifying individuals as high-risk based on autonomic dysfunction or CAN could support personalized and timely cardiovascular screening or interventions⁷³.

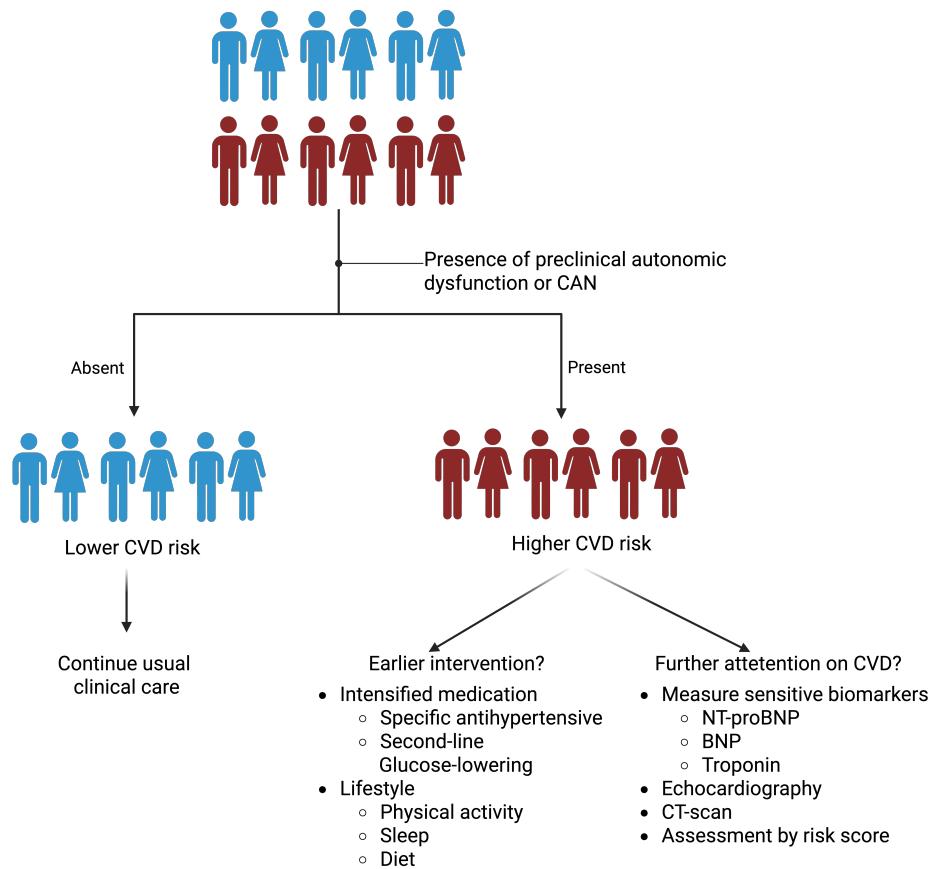


Figure 7.2: Conceptual model for risk stratification by autonomic dysfunction. (Source: Author)

7.3 Effective causal modifiable marker

Our findings support a potential etiological link between long-term HRV and CVD risk, providing preliminary evidence consistent with a causal relationship. However, the observed association does not confirm causality, and further research is needed to determine whether HRV directly influences CVD outcomes. While randomized controlled trials are the gold standard for establishing causality, isolating the direct effect of HRV is particularly challenging. Interventions that affect HRV often do so indirectly through changes in weight, inflammation, or insulin sensitivity. Similarly, pharmacological treatments

7.3 Effective causal modifiable marker

may improve HRV as a secondary effect, such as through blood pressure reduction from antihypertensive medications. This makes it difficult to determine whether modifying HRV itself leads to improved cardiovascular outcomes.

To address these limitations, modern epidemiological methods such as Mendelian randomization and structured causal mediation analysis offer promising alternatives. These approaches can help infer causality from observational data and estimate indirect effects using trial data. Notably, no GWAS has yet investigated the genetic determinants of long-term HRV. Establishing such associations is essential for understanding its genetic architecture and for using genetic variants as unconfounded proxies to assess HRV's causal role in CVD. However, a challenge arises from findings in short-term HRV, which show considerable pleiotropy. This may complicate the use of Mendelian randomization, as the method relies on the assumption of no horizontal pleiotropy¹⁴⁷.

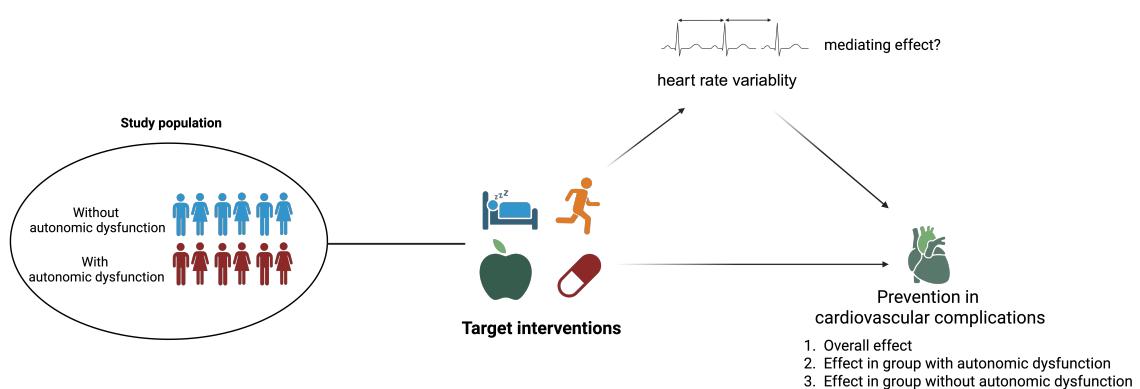


Figure 7.3: Mediation of HRV by intervention in prevention of CVD. (Source: Author)

Future cardiometabolic intervention trials and longitudinal cohorts, whether focused on lifestyle or pharmacological strategies, should, where feasible, include repeated HRV measurements. This would enable structured mediation analyses and help determine whether modifying autonomic function leads to sustained improvements in cardiovascular outcomes. Such evidence could clarify whether interventions like antihypertensive medications or lifestyle changes in physical activity, diet, and sleep can causally and sustainably improve CVD risk through HRV modulation.

8 Conclusion

This dissertation aimed to investigate how autonomic dysfunction, assessed by HRV and CARTs, is associated with cardiovascular complications across different stages of glucose metabolism. The findings support the hypothesis that autonomic dysfunction is an early and independent marker of cardiovascular risk.

Autonomic dysfunction was associated with higher arterial stiffness not only in individuals with T2D, but also in those with prediabetes and normal glucose metabolism. A particularly pronounced association was observed in individuals with prediabetes, where lower multiday HRV was linked to a higher risk of cardiovascular disease, heart failure, and mortality. These findings suggest that autonomic dysfunction may contribute to cardiovascular complications even before the onset of T2D, potentially through a modifying effect during the early stages of dysglycemia. Among individuals with T2D, standardized CARTs identified those with CAN who had a higher risk of heart failure, even when asymptomatic and not classified as high risk by risk scores.

Early detection is important, as CVD and heart failure are associated with reduced life expectancy and quality of life. This dissertation demonstrates the potential of autonomic dysfunction as a clinically relevant marker of cardiovascular risk across the full spectrum of glucose metabolism, including stages prior to the onset of T2D. However, it remains unclear whether this dysfunction plays a causal role or reflects underlying pathophysiological processes. Further research is needed to determine its clinical utility in risk stratification and its potential as a target for intervention.

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Summary

This dissertation investigated whether cardiovascular autonomic dysfunction is associated with cardiovascular complications in individuals with normal glucose metabolism, prediabetes, and type 2 diabetes. Cardiovascular autonomic dysfunction was assessed using heart rate variability and standardized cardiovascular autonomic reflex tests. Among the measures, 24-hour heart rate variability reflected autonomic balance and circadian shifts in sympathetic and parasympathetic activity. Lower long-term heart rate variability was consistently associated with adverse cardiovascular outcomes.

Across three studies, autonomic dysfunction was linked to higher levels of arterial stiffness, a higher incidence of ischemic cardiovascular events, heart failure, and all-cause mortality. The association with arterial stiffness was observed across the full spectrum of glucose metabolism and was particularly pronounced in individuals with prediabetes, suggesting that autonomic dysfunction may play a role early in the pathophysiological process. Building on this, the subsequent studies focused on individuals at high risk of developing diabetes. In this population, cardiovascular autonomic dysfunction was associated with a higher risk of cardiovascular disease, heart failure, and mortality.

Cardiovascular autonomic neuropathy, as identified through abnormal cardiovascular reflex testing, was associated with a higher risk of heart failure, even in individuals without symptoms. These findings suggest that cardiovascular autonomic dysfunction may serve as an early and independent marker of heart failure risk, particularly in populations at risk of type 2 diabetes.

The dissertation concludes that cardiovascular autonomic dysfunction is a clinically relevant risk factor that warrants further attention in both research and clinical practice. Future studies should explore whether improving autonomic function can reduce cardiovascular risk and whether measures of autonomic dysfunction can be integrated into existing risk models. Additionally, the potential of wearable technologies for continuous monitoring and early detection is a possibility to be evaluated in both clinical and general populations.

Resume

Denne afhandling undersøgte, om kardiovaskulær autonom dysfunktion er forbundet med kardiovaskulære komplikationer hos personer med normal glukosemetabolisme, præ-diabetes og type 2-diabetes. Kardiovaskulær autonom dysfunktion blev målt igennem hjeretrymevariabilitet (HRV) og standardiserede kardiovaskulære autonome refleksundersøgelser (CARTs). Blandt målingerne gav 24-timers HRV indsigt i den autonome balance og døgnrytmens skift mellem sympathisk og parasympatisk aktivitet. Lavere værdier var konsekvent forbundet med ugunstige kardiovaskulære udfald.

På tværs af tre studier blev autonom dysfunktion forbundet med højere niveauer af arteriel stivhed, en højere forekomst af iskæmiske hjertekarsygedom, hjertesvigt og dødelighed. Sammenhængen med arteriel stivhed blev observeret på tværs af hele spektret af glukosemetabolisme og var særligt forhøjet hos personer med prædiabetes, hvilket antyder, at autonom dysfunktion. På baggrund af dette fokuserede det efterfølgende studie på personer med høj risiko for at udvikle diabetes. I denne population var kardiovaskulær autonom dysfunktion forbundet med højere risiko for kardiovaskulær sygdom, hjertesvigt og dødelighed.

Kardiovaskulær autonom neuropati, defineret gennem abnormale CARTs, var forbundet med en højere risiko for hjertesvigt hos individer med type 2 diabetes, selv hos personer uden symptomer. Disse fund tyder på, at kardiovaskulær autonom dysfunktion kan fungere som en tidlig og uafhængig markør for risikoen for hjertesvigt, især i populationer med risiko for type 2-diabetes.

Afhandlingen konkluderer, at kardiovaskulær autonom dysfunktion er en klinisk relevant risikofaktor, som bør tiltrække større opmærksomhed i både forskning og klinisk praksis. Fremtidige studier bør undersøge, om forbedring af autonom funktion kan reducere kardiovaskulær risiko, og om målinger af autonom dysfunktion kan integreres i eksisterende risikomodeller. Derudover er potentialet i smarture til kontinuerlig overvågning og tidlig opsporing en mulighed, der kan vurderes i både kliniske og generelle populationer.

A Appendix

A.1 Study I