

Cardiovascular autonomic dysfunction impact on cardiovascular complications across glucose metabolism

Jonas Rosborg Schaarup

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Thanks for all the fish.

Supervisors and assessment committee

PhD student:

Jonas Rosborg Schaarup, Msc in Public Health
Department of Public Health, Aarhus University, Denmark

Supervisors:

Professor Daniel R. Witte, PhD (main supervisor)
Department of Public Health, Aarhus University, Denmark
Steno Diabetes Center Aarhus, Denmark

Lasse Bjerg, MD PhD
Department of Public Health, Aarhus University, Denmark
Steno Diabetes Center Aarhus, Denmark

Signe Toft Andersen, MD PhD
Department of Public Health, Aarhus University, Denmark Steno Diabetes Center
Aarhus, Denmark

Christian Stevens Hansen, MD PhD
Steno Diabetes Center Copenhagen, Denmark

Assessment committee:

Professor Morten Schmidt (chair and moderator of the defence) Department of Clinical Medicine - Department of Clinical Epidemiology, Aarhus University

Associate Professor Ilonca Vaartjes University Medical Center Utrecht, Julius Center, Department of Epidemiology and Health Economics

Cardiologist Peter Godsk Jørgensen Herlev and Gentofte Hospital, Capital Region of Denmark

Papers in the dissertation

Study I

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Study III

Cardiovascular autonomic neuropathy and indices of heart failure in type 2 diabetes:
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Additional publications

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Abstract

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1. Introduction [under construction]

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2. Background [needs to be fine-tuned]

2.1. Type 2 diabetes and prediabetes

The body regulates glucose and insulin to maintain glucose homeostasis. During fasting, pancreatic alpha cells secrete glucagon, which stimulates hepatic glucose production via glycogenolysis and gluconeogenesis. Meanwhile, glucose is endogenously produced by the liver and kidneys and utilized by body tissues. 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. Insulin and incretins work together to suppress hepatic glucose production, while insulin promotes glucose uptake in muscle and adipose tissue. Excess glucose is primarily stored as glycogen in the liver and muscles, with some converted to triglycerides for long-term storage. Glucose homeostasis is dynamically regulated by inhibitory factors (insulin, hyperglycemia, parasympathetic activity, and substrate availability) and stimulatory factors (glucagon, counterregulatory hormones, hypoglycemia, sympathetic activity, and gluconeogenic substrates).

The progression from normal glucose metabolism to type 2 diabetes is characterized by sustained elevations in blood glucose levels, primarily driven by insulin resistance and followed by a gradual decline in beta-cell function. Insulin resistance occurs when certain cells, such as muscle and liver cells, lose their sensitivity to insulin. As a result, glucose is not effectively taken up by these tissues and remains in blood circulation. Meanwhile, beta-cell function deteriorates, leading to a diminished insulin response to glucose intake. Years before diagnosis, these changes contribute to rising fasting and postprandial glucose levels. [note: read Omar introduction!!!]

Diabetes progression is a continuum, with type 2 diabetes defined based on glucose thresholds associated with an increased risk of diabetes-specific microvascular complications, particularly retinopathy. The WHO (2011) and ADA (2015) diagnostic criteria for type 2 diabetes include fasting plasma glucose 7.0 mmol/L, 2-hour plasma glucose 11.1 mmol/L during an oral glucose tolerance test, or hemoglobin A1c (HbA1c) 6.5% (48 mmol/mol). However, many complications of diabetes, such as macrovascular disease, neuropathy, cancer, and cognitive impairment, can begin to develop at earlier stages of dysglycemia. 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

2. Background [needs to be fine-tuned]

levels between 7.8–11.0 mmol/L (WHO criteria), and HbA1c levels between 5.7–6.4% (39–47 mmol/mol) (ADA criteria) [ref.].

Risk factors for progression to type 2 diabetes and its complications range from genetic predisposition to lifestyle and socio-environmental factors. The most common precursor to diabetes is central obesity, characterized by excess body fat. The accumulation of diabetes risk factors is linked with a combination of adverse changes in cardiometabolic markers, including increases in low-density lipoprotein (LDL) cholesterol, triglycerides, body mass index (BMI), and systolic blood pressure, along with decreases in high-density lipoprotein (HDL) cholesterol. [Lancet Diabetes Endocrinol 2013; 1: 43–51].

Diabetes increases the risk of both microvascular and macrovascular complications, which are major determinants of the disease's associated morbidity and mortality. Diabetes and cardiovascular disease share common risk factors, including lifestyle factors and conventional clinical markers. As individuals progress toward diabetes, their cardiovascular risk increases, making them more susceptible to developing cardiovascular disease (CVD). However, the identification of preclinical stages of CVD and how CVD risk differs among individuals at high risk of diabetes and individuals with type 2 diabetes needs further definition.

2.2. Cardiovascular disease

Globally, CVD remains the leading cause of death. However, the main cause of mortality varies by country income levels, with cancer becoming the leading cause in some high-income countries. CVD risk is primarily attributable to modifiable lifestyle behaviour such as stress, sedentary behaviour, unhealthy diet, alcohol consumption, and smoking, as well as socio-environmental factors like socio-economic status and air pollution¹. Along the causal pathway towards CVD, these risk factors contribute to comorbidities such as clinical obesity, diabetes, hypertension, and hypercholesterolemia, further accelerating overall CVD risk. While risk factors are largely shared across CVD types, the mechanisms differ, involving structural, signalling, inflammatory, and dynamic changes in the cardiovascular system.

2.2.1. Arteriosclerosis

Hard CVD end-points are the primary focus of CVD prevention measures. However earlier markers of arterial stiffness assess the gradual vascular pathology and reflect arteriosclerosis, atherosclerosis, vascular calcification. With aging, elastin fibers are gradually replaced by collagen fibers, leading to increased vascular stiffness². Arterial stiffness

is characterized by changes between collagen, elastin, and smooth muscle cells. Stiffening of the arterial vasculature increases systolic pressure, reduces coronary perfusion, and raises the pulsatile load on the micro- and macrocirculation. This process can be accelerated by modifiable CVD risk factors. The progression of arterial stiffness is an early marker in the trajectory of CVD development, as increased stiffness precedes rises in blood pressure and CVD.

2.2.2. Atherosclerosis

Atherosclerosis is characterized by plaque build-up in the arteries, which can develop into a thrombus, leading to artery blockage or haemorrhage. The underlying process of atherosclerosis is where cholesterol, fat, and other substances accumulate in the arterial walls, causing narrowing and reducing blood flow to the heart. When the oxygen supply to the heart is insufficient, it can result in chest pain (angina) or, in severe cases, myocardial infarction. Over time, chronic ischemia can lead to structural and functional changes in the heart, increasing the risk of heart failure and arrhythmia.

Myocardial infarction

Myocardial infarction (MI) occurs due to the rupture of an atherosclerotic plaque in the coronary arteries, triggering thrombus formation that blocks blood flow. This leads to oxygen deprivation (ischemia) and subsequent myocardial injury or necrosis. If untreated, this process can cause extensive cardiac damage and fatal arrhythmias. Over the past decades, the incidence rate of MI has decreased in high-income countries, while improvements in early detection and treatment (both intravenous and therapeutic) have led to a steep decline in MI-related mortality. These advancements have also contributed to a lower prevalence of individuals living with prior MI. In type 2 diabetes, the risk of MI is elevated by 72%, with an approximately threefold risk among patients under 60 years compared to age under 60 without type 2 diabetes³. Similar to the general population, its incidence and fatality have declined in diabetes.

Stroke

Stroke is a cardiovascular disease that can be either ischemic or hemorrhagic. The majority of strokes are ischemic, caused by an obstruction in a cerebral artery, often due to an atherosclerotic plaque or embolism. 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 and increased intracranial pressure⁴. Ischemic stroke remains one of the global leading contributor to mortality and disability⁵. The incidence, prevalence, and cause-specific mortality of stroke remain high but have stagnated, although some declines have been observed in

2. Background [needs to be fine-tuned]

high-income countries⁶. Stroke risk is already elevated at high levels of glucose (fasting plasma, OGTT, and HbA1c) among people in a pre-diabetic range where the risk exceed of 26% higher risk compared to population without diabetes [7]⁸. In type 2 diabetes, the ischemic stroke risk is elevated almost two-fold³.

2.2.3. Heart failure

Heart failure develops gradual with age and often accelerates with the progression of type 2 diabetes. As treatment of ischemic CVD events has improved survival over the last years, the incidence and prevalence of heart failure has increased. Therefore, early detection are important as heart failure leads to lower life-expectancy and quality of life.

Heart failure is commonly classified as either ischemic or non-ischemic in origin. It may arise as a consequence of atherosclerosis, arteriosclerosis, or both, contributing to myocardial ischemia, pressure overload, and structural cardiac changes. Heart failure is a clinical condition characterized by symptoms of breathlessness, fatigue, and fluid retention, often accompanied by clinical signs such as pulmonary crepitations, jugular venous elevation, and peripheral edema. Heart failure can also 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. Therefore, it is a complex cardiovascular disease caused by structural and functional changes in the heart musculature, affecting systolic and/or diastolic pumping function. Heart failure is generally classified into two subtypes: heart failure with reduced ejection fraction (HFrEF) and heart failure with preserved ejection fraction (HFpEF). Both subtypes involve cardiac remodeling but are defined by left ventricular ejection fraction (LVEF). HFrEF is characterized by an LVEF<40%, while HFpEF has LVEF 50% but have multiple abnormalities in parameters from echocardiogram. HFrEF is often followed by ischemic caused heart failure.

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 reserve⁹. 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. It is diagnosed based on abnormal echocardiographic measures of, e.g., left ventricular hypertrophy, left atrial enlargement, or elevated filling pressure¹⁰. 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

2.3. Cardiovascular autonomic dysfunction

pro-B-type natriuretic peptide (NT-proBNP) or brain-neuretic-peptide (BNP). As a result, HFpEF is commonly underdiagnosed and consequently detected at more severe stages, leading to hospitalization¹⁰.

2.3. Cardiovascular autonomic dysfunction

The cardiovascular system is regulated by autonomic nervous system which influences heart rate and vasoconstriction through neurotransmitter release by the sympathetic and parasympathetic nerves. The primary neurotransmitter of the sympathetic nervous system is noradrenaline, while the parasympathetic nervous system primarily releases acetylcholine by stimulation through the Vagus nerve. 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. It also slows AV nodal conduction, predominantly via the left vagus nerve, thereby prolonging atrioventricular conduction time. Afferent 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 homeostasis in response to physiological demands, such as rest and physical activity.

[insert figure of brain heart and sympathetic nerves]

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, metabolic-related conditions such as obesity and diabetes have been shown to further contribute to autonomic dysfunction. Autonomic dysfunction reflects a stressed cardiometabolic environment, as both dysfunction in lipid and glucose metabolism are associated with increased sympathetic activity¹¹. 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 metabolism¹¹. Therefore, the relationship between autonomic dysfunction and cardiometabolic factors is likely a vicious cycle¹². The consequences can lead to cardiovascular autonomic dysfunction/neuropathy (CAN), resulting dysregulation in heart rate and vascular dynamics. In this thesis, we will use ‘cardiovascular autonomic dysfunction’ as the broader term, while ‘CAN’ will refer specifically to autonomic dysfunction resulting from neuropathy in type 2 diabetes.

2. Background [needs to be fine-tuned]

Cardiovascular 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. 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 (diurnal) pattern¹³. Most studies have examined cardiovascular autonomic function using short-term ECG recordings at rest. 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). Heart rate variability [from physiology to psychology, to cardiovascular research, to diabetes research]. Type 2 diabetes has shown to significantly modify the expression of sympathetic bursts, measured by resting muscle sympathetic nerve activity, and even higher when co-existing with hypertension compared to normotensive without diabetes¹⁴. Parasympathetic activity is as well deteriorated among high cardiometabolic risk, and type 2 diabetes, shown by impaired baroreflex sensitivity¹⁵ and lower HF and RMSSD short-term HRV. 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 [¹²]¹⁶. Cardiovascular autonomic reflex tests (CARTs) are considered the gold standard for assessing CAN. 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. Both HRV and CARTs have been associated with cardiovascular disease, heart failure, and all-cause mortality, primarily in populations with type 2 diabetes or established cardiovascular disease. 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 type 2 diabetes. The 2022 ADA/EASD guidelines for the management of hyperglycemia in type 2 diabetes recommend, cardioprotective medication GLP-1 receptor agonists and SGLT2-inhibitors as first-line options for individuals at high cardiovascular risk. 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 albuminuria. However, no additional preclinical markers are recommended to identify individuals at higher CVD or HF risk. Despite their increased risk of cardiovascular

2.4. Risk-stratification

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 [17]18. During the progression and after the onset of type 2 diabetes, preclinical stages may manifest with markers of higher cardiovascular risk, underscoring the potential for risk stratification. Risk stratification is the process of classifying individuals based on risk scores, biomarker levels, omic data (metabolomic, proteomics, and genomic) or pre-clinical conditions. This approach aids in subtyping patients for prognostic or diagnostic purposes, identifying subgroups that require further evaluation, intensified treatment, or lifestyle modifications.

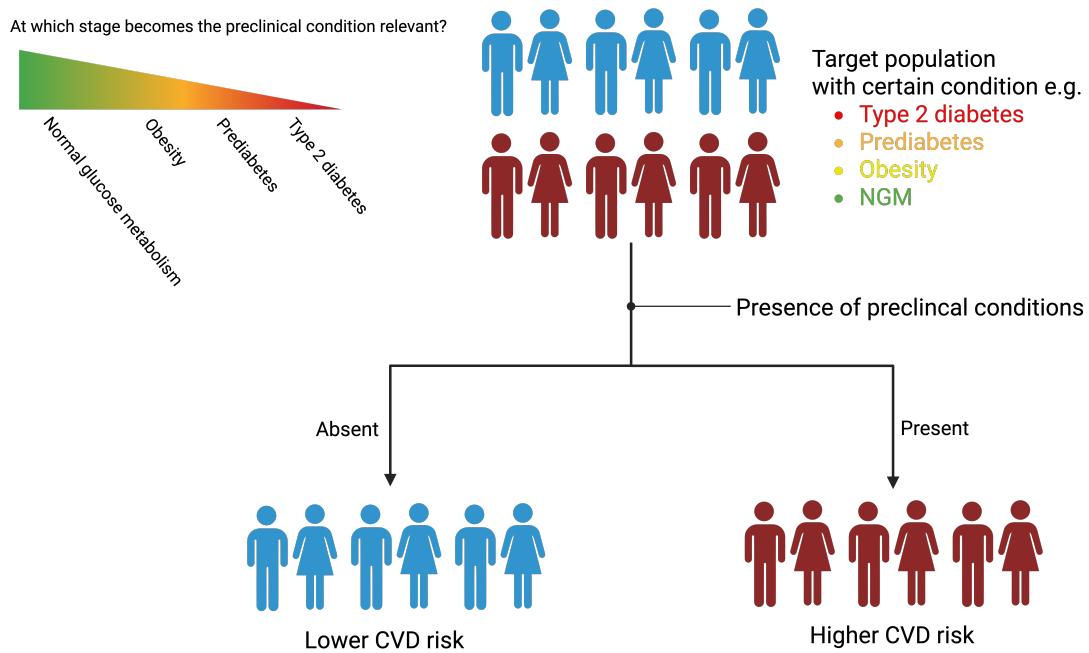


Figure 2.1.: Risk-stratification based on preclinical disease

Cardiovascular autonomic dysfunction despite its relationship with cardiovascular complication has not been defined into clinical practice. Larger epidemiological cohort studies encompassing various stages of diabetes risk, from normal glucose metabolism to prediabetes, onset of type 2 diabetes, and longer term progression of type 2 diabetes, serve as valuable resources for identifying risk-stratification opportunities. Epidemiological studies provide a broad representation of the target population, allowing understand the relationship between cardiovascular autonomic dysfunction and cardiovascular complications. They also have potential to determine when, along the trajectory of diabetes

2. Background [needs to be fine-tuned]

progression and duration, autonomic function are meaningful for cardiovascular risk-stratification.

2.5. Aetiological research

Aetiology seeks to identify the causes and contributing factors of disease, forming the foundation for understanding its development and underlying mechanisms. Ideally, to determine causal effects, we would compare outcomes in individuals who were exposed to a risk factor with what would have happened if they had not been exposed. Since this counterfactual scenario is impossible to observe directly, we rely on study designs, such as randomized controlled trials when feasible, and apply statistical methods to data from observational cohort studies to approximate these comparisons. In cardiovascular disease, socio-environmental influences and personal health behaviours play a crucial role in overall health and are considered the outer contributing layer to biological mechanism. The inner layer focuses on biological causal processes, where the connection between these contributing factors and individual predisposition to cardiovascular disease remains a key question in understanding the underlying pathological mechanisms.

Cardiovascular autonomic dysfunction is linked to CVD and all-cause mortality. However, many questions remain regarding the underlying causal mechanisms. Furthermore, as dysglycemia is known to be a primary driver of autonomic dysfunction¹⁹, the question is to which extent it modulates the relationship between cardiovascular autonomic dysfunction and CVD? This relationship remains unclear, highlighting the need for a deeper understanding of this interplay in target populations representing different stages of glucose metabolism.

3. Aim and hypothesis

The overall aim of this PhD is to understand how cardiovascular autonomic dysfunction/neuropathy (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.

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 normoglycemia, prediabetes or type 2 diabetes.

Study II: Quantify the longitudinal association of week-long and hourly HRV with incidence ischemic-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 (Pro-BNP), WATCH-DM risk, and New York Heart Association (NYHA) scores among individuals with type 2 diabetes.

The hypotheses of this dissertation are:

CAN and autonomic dysfunction is associated with CVD and acts as an early risk factor for heart failure and other cardiovascular complications, including stroke, and myocardial infarction in patients with prediabetes and/or type 2 diabetes. In addition autonomic dysfunction is associated with higher levels of carotid-femoral pulse wave velocity and carotid artery distensibility.

4. Materials and methods [needs to be fine-tuned]

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 type 2 diabetes: The CANCAN study
Design	Aetiological cross-sectional study	Aetiological prospective cohort study	Descriptive cross-sectional study
Cohort	Maastricht study	ADDITION-PRO	CANCAN
Study	3673 people with normal glucose metabolism, prediabetes, and type 2 diabetes	2082 people with high risk of diabetes	173 patients with type 2 diabetes 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	Week-long and hourly HRV	Cardiovascular autonomic reflex test NT-proBNP
Primary outcome	Arterial stiffness	Major adverse cardiovascular events, heart failure, and all-cause mortality	

4.1. Overview of the studies

Study I	Study II	Study III
Statistical analysis Missing data	Linear regression Complete case analysis	Poisson regression
	Multiple imputation of chained equations for confounders	Logistic regression Complete case analysis and multiple imputation of chained equations for CART and confounders

4.1.1. Study population

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 type 2 diabetes, through the regional Diabetes Patient Registry, to extensively phenotype individuals with type 2 diabetes 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 population 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 informed consent.

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, originally designed as a stepwise screening program for type 2 diabetes in general practice. ADDITION-PRO aims to investigate early markers of cardiovascular disease (CVD) and metabolic dysfunction in individuals in different tiers of diabetes risk.

4. Materials and methods [needs to be fine-tuned]

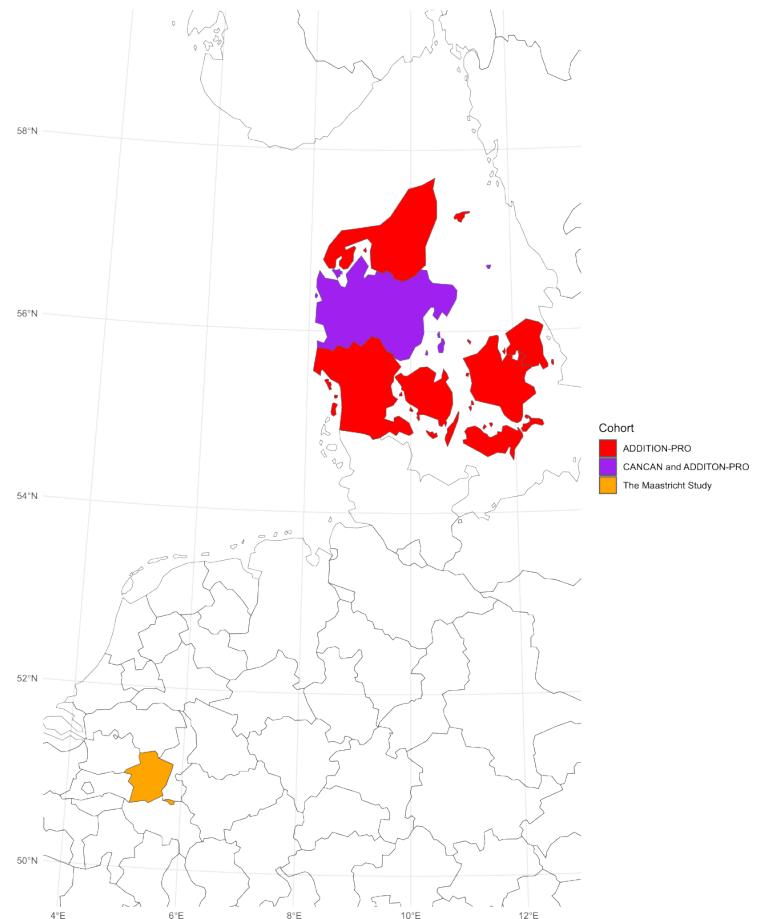


Figure 4.1.: Study populations

4.1. Overview of the studies

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 type 2 diabetes, identified through a stepwise screening program that incorporated the Danish diabetes risk score from the Inter99. 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 type 2 diabetes by blood measurements including HbA1c, random blood glucose, FPG, and OGTT, were identified patients were invited to the ADDITION-trial. High risk individuals without type 2 diabetes 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 longitudinal cohort. 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 disorder 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 ActiHeart, which recorded acceleration and heart rate over a week. In study II, we included participants with a least 48-hour recording for our first analysis, and then include those participants with hourly measures of physical acceleration during the hourly HRV recording for th second analysis. We also excluded participant with prior CVD ten years before inclusion.

The population were disease history and follow-up in the unique register system of Denmark, 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. Materials and methods [needs to be fine-tuned]

4.1.1.3. Study III - CANCAN

The CANCAN Study is an observational pilot 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 type 2 diabetes in Central Denmark. We included 200 adults (>18 years) with type 2 diabetes with 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 cardiovascular autonomic dysfunction/ neuropathy

Heart rate variability

In study I-III a device was 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 HRV. The pool of hearbeat data, we extrapolated time-domain and frequency-domain HRV indices. In study III, we used the ratio in pulse rate in test under different conditions lying-to-standing, in- expiration, and valsalva maneuvre.

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 box 1.

Table 4.2.: Box 1: Time-domain HRV indices

Time-domain HRV	Description
Standard deviation of NN heart beat intervals (SDNN, in ms)	Reflects overall HRV and total autonomic nervous system activity over the recording period.

4.2. Study variables

Time-domain HRV	Description
SD of the averages of NN intervals in 5-minute segments throughout the recording (SDANN, in ms)	Measures long-term HRV variations, primarily reflecting circadian and autonomic fluctuations.
Mean of the SDs of all NN intervals for all 5-minute segments (SDNN index, in ms)	Estimates short-term HRV fluctuations and vagal tone by averaging segmental variations.
NN50 count divided by the total number of all NN intervals (pNN50, percentage)	Represents the proportion of successive NN intervals differing by more than 50 ms, indicating vagal activity.
Square root of the mean of the sum of squares of differences between adjacent NN intervals (RMSSD, in ms)	Reflects short-term HRV, mainly parasympathetic (vagal) activity.

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 box 2.

Table 4.3.: Box 2: Frequency-domain HRV indices

Frequency domain HRV	Description
Variance of all NN intervals 0.4 Hz, total power (TP, in ms²)	Represents overall HRV, reflecting both short- and long-term autonomic regulation.
Ultralow-frequency range (ULF, in ms²; 0.003 Hz)	Captures very long-term oscillations, influenced by circadian rhythms, metabolism, and thermoregulation.
Very-low-frequency range (VLF, in ms²; 0.003–0.04 Hz)	Associated with sympathetic activity, inflammation, and hormonal regulation.
Low-frequency range (LF, in ms²; 0.04–0.15 Hz)	Reflects a mix of sympathetic and parasympathetic activity, often linked to blood pressure regulation and baroreflex sensitivity.

4. Materials and methods [needs to be fine-tuned]

Frequency domain HRV	Description
High-frequency range (HF, in ms²; 0.15–0.4 Hz)	Represents parasympathetic (vagal) modulation of heart rate, closely related to respiratory sinus arrhythmia.

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 intervals to validate our algorithm²⁰. 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). Three standardized CARTs were performed: lying-to-standing, deep breathing, and the Valsalva manoeuvre, following a standardized protocol between 8:00 a.m. and 2:00 p.m. after 10 minutes of supine

4.2. Study variables

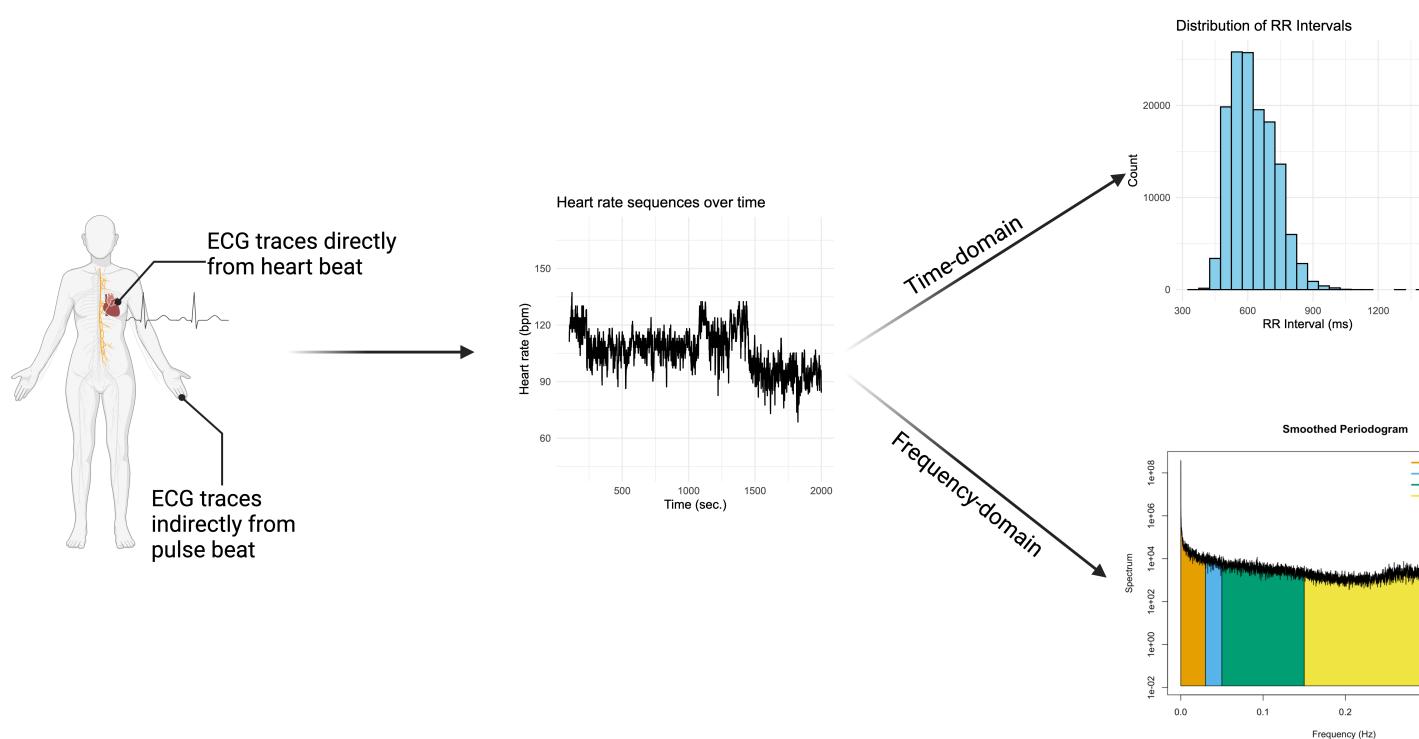


Figure 4.2.: Heart rate variability

4. Materials and methods [needs to be fine-tuned]

rest. Smoking and caffeine intake were prohibited two hours before testing. Each test was conducted once by trained examiners.



Figure 4.3.: Handheld Vagus™ device

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.).

Cardiovascular autonomic reflex test



Figure 4.4.: CART

HRV was derived from all CARTs using autoregressive spectral analysis. Time domain measures included SDNN and RMSSD, while frequency domain measures included LF, HF, and total power. 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.).

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

4.3. Outcomes

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, type 2 diabetes) 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 cardiovascular disease (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

Pulse wave velocity

Arterial stiffness can be characterized by measuring arteriosclerosis and atherosclerosis properties of the arteries. The stiffness of different trees of the vascular musculature can assessed both locally and dynamically. Aortic and carotid stiffness were assessed as markers of arterial stiffness, following previously described procedures. Aortic stiffness was measured by carotid-femoral pulse wave velocity (PWV) using applanation tonometry (SphygmoCor, Atcor Medical, Sydney, Australia), with the median of at least three consecutive recordings included in the analysis.

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 $\Delta D/braPP$, where ΔD represents carotid distension and braPP is brachial pulse

4. Materials and methods [needs to be fine-tuned]

pressure. Mean heart rate and mean arterial pressure (MAP) were recorded every five minutes using an oscillometer device (Accutorr Plus, Datascope, Montvale, NJ, USA).

[insert figure of PWV and CD]

4.3.2. Biomarker 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. It derives from B-type natriuretic peptid (BNP) which is a cardial neurohormon, that is syntezied and secreted as response to streched cariomcytes 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, blood sample were taken at study cite. Description of the NT-proBNP analysis of plasma samples is described in supplementary material [ref].

4.3.3. Cardiovascular events

Information on CVD events and mortality was obtained from the Danish National Patient Registers until 2021. 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.

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

4.4. Statistical Methods

4.4.0.1. Cross-sectional analysis

In study I, we used multiple linear regression to investigate associations between week-long 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 type 2 diabetes and potential instrumental bias of arterial pressure flow. Model 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. We add interaction sex to observe if the association differed between sex. We performed sensitivity analyses excluding individuals on antihypertensive treatment or glucose-lowering medication. 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 excluded participants with beta-blocker treatment or prior CVD.

4.4.0.2. 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 modifier. This means that the observed relationship between the exposure and the outcome is not uniform across all subgroups. Instead, it differs across strata defined by the effect modifier²¹.

In study I, we hypothesize that the association between 24-hour and arterial stiffness was stronger in strata of progression of diabetes (normal glucose metabolism, prediabetes, type 2 diabetes). We therefore first stratified by diabetes status to observe the size of the association across strata. We then combine all groups and include an interaction term between HRV and diabetes status. We did subsidiary analysis to check if the effect was modified by dysglycemia by stratifying HbA1c and fasting plasma glucose into deciles. In Study II, we quantified whether the association between multiday HRV and CVD endpoints varied by sex 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, we hypothesized no significant effect modification between groups with and

4. Materials and methods [needs to be fine-tuned]

without symptoms. Similarly, we explored whether the association remains present in the group classified as low to moderate risk of heart failure, 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.

4.4.0.3. 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 hazards²². Week-long 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.

4.4.1. 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, we followed Rubins Rule. 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, we imputed confounders to include as many participants and avoid excluding population with our without cardiovascular or mortality events. We imputed dataset 10 times. In study III, we imputed missing CART, 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 bias²³. 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.

4.4.2. 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 cardiovascular autonomic function using week-long 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 failure. We adjusted the model to account for the blurred effect of eGFR on NT-proBNP levels in the analysis.

5. Results [needs to be fine-tuned]

In this section, I will summarize study population characteristics and findings from analysis.

5.1. Study I

5.1.1. Descriptive

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

5.1.2. 24-hour HRV and arterial stiffness

Time-domain HRV

In the fully adjusted model 2, PWV was 2.8% (CI: 2.1; 3.4) lower, while CD was 3.3% (CI: 1.5; 5.1) higher per SD increase in HRV time-domain Z-score. 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), respectively. 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 CD.

Frequency-domain HRV

In the fully adjusted model 2, PWV was 2.8% (CI: 2.1; 3.5) lower, while CD was 3.2% (CI: 1.3; 5.1) higher per SD increase in HRV frequency-domain Z-score. 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;

5.1. Study I

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)
RMSD (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%)

2.6), respectively. 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 CD.

5.1.3. Effect modification of diabetes status

The study population represented diabetes risk of normal glucose metabolism (65%), prediabetes (15%), and type 2 diabetes (20%). The median (IQR) cf-PWV (aortic stiffness) increased with diabetes status: NGM: 8.08 m/s (7.28, 9.16), prediabetes: 8.96 m/s (7.84, 10.32), and type 2 diabetes: 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 type 2 diabetes: 12.5 (9.9, 16.0) $\times 10^{-3}$ /kPa. SDNN (ms) was highest in NGM and decreased with worsening glucose metabolism: NGM: 138ms (117, 164), prediabetes: 127ms (106, 152), and type 2 diabetes: 116ms (96, 139).

The association between HRV time-domain Z-scores and cf-PWV and CD was significantly modified by prediabetes (PWV: -4.9 [CI: -6.523; -3.243] $interaction(*)^{p-value < 0.01}$ CD: 8.0 [CI: 3.8; 12.5] $^{*p-value < 0.01}$) but not by type 2 diabetes (PWV: -3.5 % [CI: -4.8; -2.1])

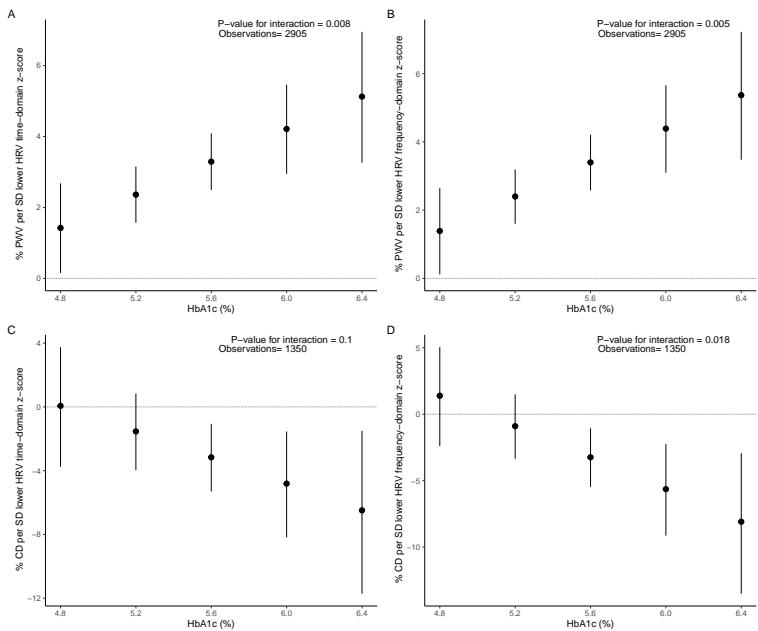
5. Results [needs to be fine-tuned]

* $p-value < 0.1$ CD: 4.8 % [CI:1.3; 8.4]* $p-value < 0.1$). For the indices SDNN and SDANN, the association with both cf-PWV and CD was significantly modified by both prediabetes and type 2 diabetes.

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]* $p-value < 0.01$) and type 2 diabetes (-3.9 %[CI:-5.4; -2.3]* $p-value < 0.05$) while CD was only modified by prediabetes (8.3 %[CI:3.6; 13.2]* $p-value < 0.01$) but not by type 2 diabetes (5.3 %[CI:1.4; 9.4]* $p-value < 0.1$). For the indices total power and ULF, the association with both cf-PWV and CD was significantly modified by both prediabetes and type 2 diabetes. Mean inter beat interval association with cf-PWV or CD was not significantly modified by diabetes status.

As we did not observe a stepwise increase in the modification of glucose metabolism status from prediabetes to type 2 diabetes, we excluded the subgroup with type 2 diabetes 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 x). 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 xB). 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 xD). No association between HRV frequency domain Z-score and CD was observed at HbA1c levels between 4.8% and 5.2%.

5.2. Study II



5.2. Study II

5.2.1. Descriptive

In ADDITION-PRO population consisted of 1,627 participant with a 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%). We splitted SDNN 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).

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.

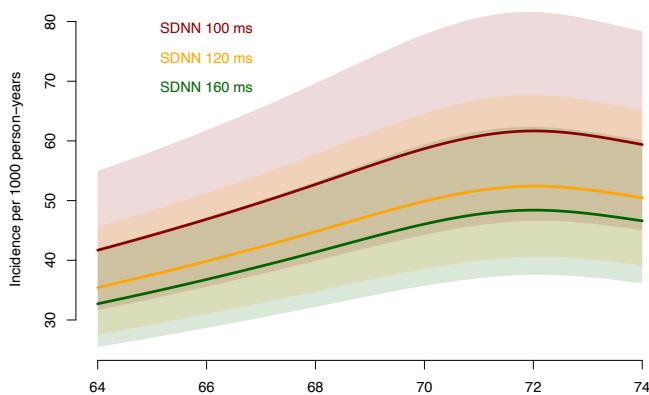
5. Results [needs to be fine-tuned]

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_antihypertensive	753 (47%)	88 (61%)	149 (48%)	216 (47%)	147 (43%)	153 (43%)

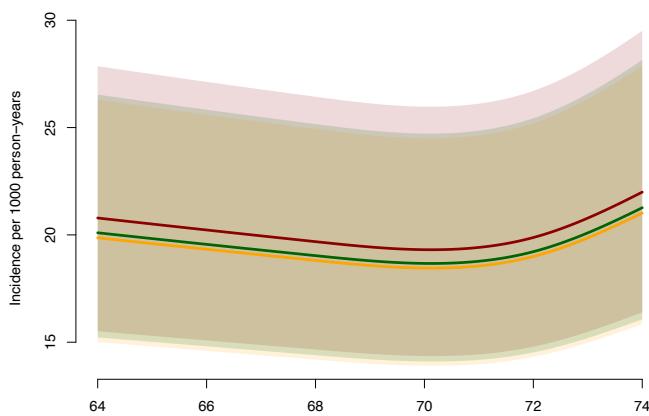
5.2.2. Week-long HRV and MACE, heart failure, and all-cause mortality.

The mean week-long SDNN was 139.0 (32.3) ms, and the mean heart rate was 73.5 (9.1) bpm. 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). When we pre-adjusted for resting heart rate, the proportion of the association explained between HRV and MACE, HF, and all-cause mortality was 14%, 25%, and 19%, respectively. We included knots in the model, which showed that the risk increased when SDNN fell below 120 to 110 ms (approximately below the 20th percentile), suggesting a potential cut-off point for higher risk. We therefore calculated the incidence rate (IR) at SDNN levels of 100 ms, 120 ms, and 160 ms, respectively, and plotted these as a function of age. :: {.center}

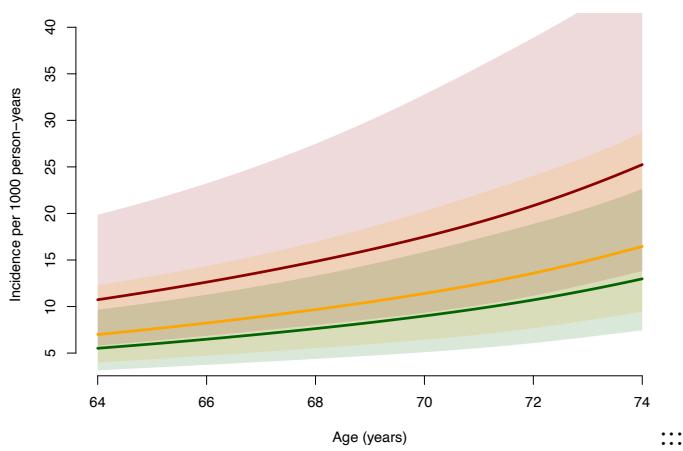
A) Major adverse cardiovascular events



B) Hospital diagnosed heart failure



C) All-cause mortality



⋮

5. Results [needs to be fine-tuned]

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 xA). 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 xB). 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 xC). 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, we observed a clear periodicity in SDNN, mean heart rate (HR), sleep patterns, and physical acceleration. SDNN increased from 5–6 AM, peaking at 8–9 AM [mean (SD)], followed by a gradual decline, reaching its lowest point around 1 AM the next day [mean SDNN (SD)]. A similar circadian pattern was observed in heart rate, though its peak occurred two hour later at 10–11 AM. After peaking, heart rate remained stable throughout the afternoon before gradually decreasing.

5.3. Study III

5.3.1. Patients characteristics

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). 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 ($n = 21$). Compared 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 type 2 diabetes (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. Study III

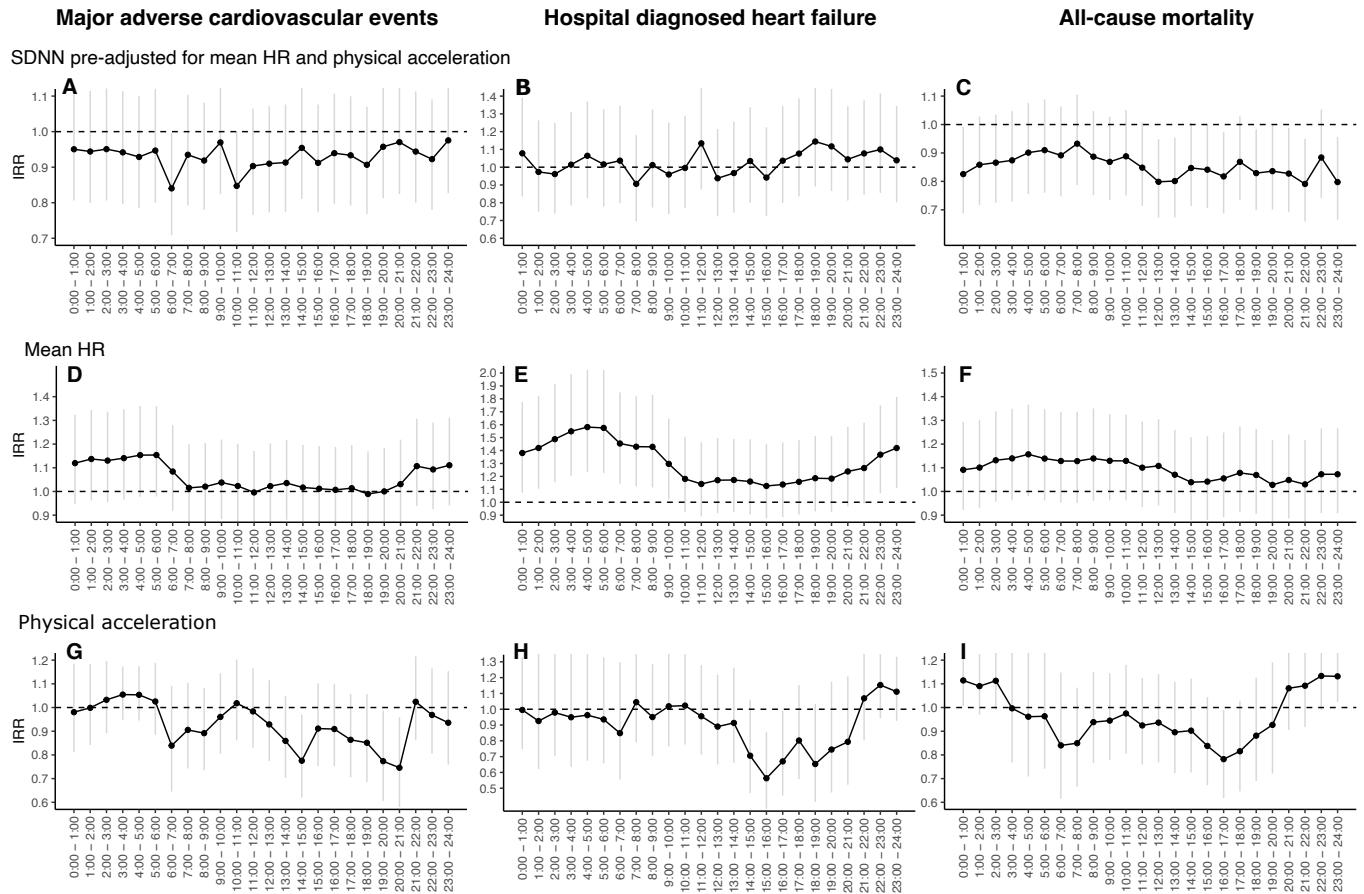


Figure 5.1.: Hourly SDNN levels (100 ms, 120 ms, 160 ms) by age-specific incidence rates for A) major adverse cardiovascular events, B) heart failure, and C) all-cause mortality. Figure adapted from [authors]. —. (Paper II, appendix)

5. Results [needs to be fine-tuned]

5.3.2. Relationship between CAN and elevated NT-proBNP

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). 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 CAN. 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). No significant association was identified for the lying-to-standing test (OR 0.80, 95% CI: 0.32, 1.97; n=54/108). 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 unchanged.

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5.3. Study III

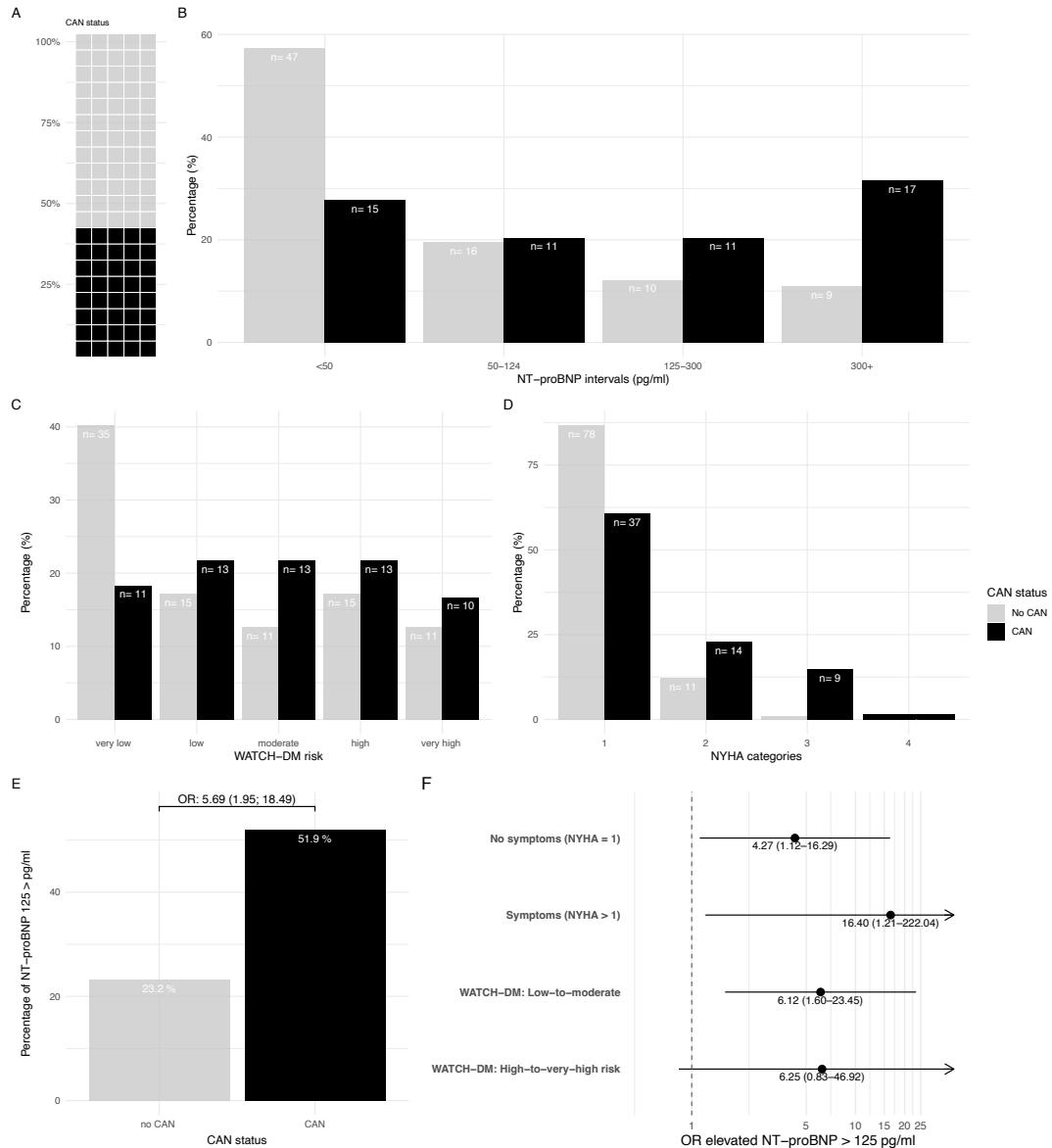


Figure 5.2.: Relationship between CAN and indicators for heart failure. Figure from [authors]. Cardiovascular autonomic neuropathy and indices of heart failure in type 2 diabetes: The CANCAN Study. (Paper III, appendix)

6. Discussion [needs to be fine-tuned]

6.1. Strength and limitation

6.1.1. 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 temporarily or confirm whether changes in the outcome were caused by the exposure. However, based on prior evidence, we assume the direction of the studies based on physiological knowledge and *in vivo* studies. In Study I, we based our direction of the association based on longitudinal association based on data from Whitehall II study, showing steeper decrease in short-term HRV are associated with subsequent higher levels of cf-PWV²⁴. Moreover, [insert *in vivo* studies]. In Study II, we attempted to mimic temporarily by glucose metabolism, in individuals with type 2 diabetes and without known type 2 diabetes, instead of time, which shows deterioration of glucose metabolism increases the size of the association. The strength of study I, is that sample size is large, making our results more generalisable to wider populations across statuses of glucose metabolism.

In study III, our study design are more focused on the clinical diagnosis of CAN and presence of heart failure. This the question are more focused on clinical utilization of CAN in detecting type 2 diabetes patients who early progress towards heart failure, and thus the aetiological question remain for other study design. Indeed, whether cardiac function progressively worsens due to the etiological mechanisms of CAN remains to be fully established. If confirmed, this would underscore the relevance of CAN as a preclinical marker for early progression to heart failure, one that may be effective to target in efforts to prevent or delay the development of overt heart failure.

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

6.1. Strength and limitation

temporal structure ensures that the exposure (HRV) clearly preceded the outcome, reducing the risk of reverse causation. Although repeated measurements of HRV over time would provide more detailed insights into autonomic function dynamics, the prospective design still allows for stronger inference of directionality than cross-sectional studies. Furthermore, the use of high-quality registry data for outcome ascertainment ensures complete follow-up and minimizes loss to follow-up bias.

Based on our studies, we demonstrate first steps in relationship between cardiovascular autonomic function, measured by, heart rate variability or CART, we can only establish an association and cannot conclude with certainty that improvements in HRV measures lead to a reduction in cardiovascular risk. Therefore, we cannot ascertain causal effect based on our findings, and more causal focused methods are needed. Mendelian randomization, which uses genetic instruments for exposure, could help address this causal question. Furthermore, structured mediation analysis involving modification, e.g. by medication or lifestyle, would improve HRV or CART leads to reduction in cardiovascular risk, using data from intervention studies.

6.1.2. Intern validity

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

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

[Actiheart and Holter monitor]

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 as a consequence to cardiac complications, and in diabetes research as a marker of autonomic neuropathy. In the context of this project, which focuses on long-term HRV in diabetes and cardiovascular research, 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, use of medication, and

6. Discussion [needs to be fine-tuned]

prior cardiovascular complications which can potentially masking or mimicking underlying physiological dysfunction during recordings. Therefore, reduced long-term HRV cannot be interpreted solely as a marker of autonomic function. Moreover, HRV is also influenced by lifestyle patterns over time, making it sensitive not only to acute behaviors but also to long-term habits that affect autonomic balance. In study II, we observed that the lower ranges of HRV had both lower habitual physical activity and lower VO₂ max, suggesting that lower HRV reflects more sedentary lifestyle and lower cardiorespiratory fitness.

In study I and II, we strived to account for habitual physical activity, while in study II, we also accounted hourly HRV for physical movement during the recording to test the influence of concurrent physical activity. However, further studies are need to understand how lifestyle patterns affect the long-term recording the subsequent day, to understand the behavioral component in long-term HRV. In study I and II, we also excluded participants with prior CVD to ensure that in order to keep etiological order between autonomic dysfunction and the outcome of cardiovascular complication.

Anti-hypertensive medications, especially beta-blockers, are known to increase HRV in randomized controlled trials²⁵. However, in cohort studies, participants using anti-hypertensives generally show lower HRV, likely reflecting their higher burden of cardiovascular complications [ref]. Because beta-blockers target the autonomic nervous system, some anti-hypertensive medications may introduce bias in HRV measurements, as they interfere with the autonomic function we aim to assess. In the sensitivity analysis in study I and III, without participants on anti-hypertensive treatment, the estimates did not materially change, thus we included the population and adjusted for medication in the full model

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

6.1.2.2. Cardiovascular autonomic reflex test

CART offers a practical approach to screening for autonomic dysfunction, as the test has been shown to be reliable²⁶. While some CART indices may be influenced by the time of day or recent physical activity, these effects are generally considered minimal. Additionally, no impact of caffeine intake on the reference age-specific values was observed²⁷.

6.1.2.3. Measures of cardiovascular risk

[Arterial stiffness - NT-proBNP - MACE limitation in aetiological research - Non-specific heart failure and MI and stroke and death - HRV stronger link with MI or stroke - Perspective: decreasing number of events with prolonging time-to-event - Clinical trial moved to high risk population in lower-income countries (South America) - Challenge for coming observational cohorts (need to increase sample size) [The Problem With Composite End Points in Cardiovascular Studies The Story of Major Adverse Cardiac Events and Percutaneous Coronary Intervention]]

6.1.3. External validity

6.1.3.1. Selection bias

The Maastricht Study

In Study I, participants were recruited using different strategies, with a focus on enrolling individuals with type 2 diabetes to ensure sufficient statistical power in this group. Recruitment was conducted through mass media campaigns, municipal registries, and the regional Diabetes Patient Registry via mailings. Thus, participation depended on individuals' awareness of the campaigns and their willingness to attend. Patients with type 2 diabetes were actively targeted with additional mail invitations to encourage participation.

ADDITION-PRO

In Study II, participants were recruited through a stepwise screening procedure. First, they were selected based on a risk score by self-administered questionnaire sent by mail, followed by HbA1c or random glucose measurements. These procedures introduce different steps for selection bias as people have both to receive and send a filled questionnaire, followed by a visit for blood testing if their risk score was high²⁸.

First, the population consists of participants who responded to the screening questionnaire and those at higher risk who underwent further blood measurements. Second,

6. Discussion [needs to be fine-tuned]

the questionnaire itself selects participants based on a risk score developed to identify individuals with type 2 diabetes, while prediabetes identification was based on further measurement on the basis of HbA1c measurements. Certain risk factors, such as age and hypertension, contribute to higher risk by influencing the risk score, and thus may lead to high representation of these groups.

Hence, selection bias arises from both participation in the risk score assessment and follow-up attendance in ADDITION, as well as from the instruments used to identify risk—namely, the Inter-99 risk score, HbA1c, and random blood glucose measurements. Healthier people are more attentive in screening and cohort studies [ref.].

CANCAN

In Denmark, patients with type 2 diabetes are referred to diabetes specialists at outpatient clinics when their general practitioner is unable to stabilize their diabetes care. As a result, CANCAN participants represent a higher-risk group in Danish diabetes patients, where more stable patients remain under general practitioner care. Consequently, the prevalence of heart failure indicators and CAN is likely higher in this selected group. The strength of the CANCAN sampling strategy in outpatient clinics is that patients were referred to an endocrinologist and attended their consultations. The additional study examination did not require extra transport or appointments but only involved additional time during their visit, with the option of receiving feedback on continuous glucose monitoring.

Overall in this project, the selection bias span across different aspects. In Study I-II, healthier and more health-conscious individuals tend to participate in cohort studies, potentially introducing selection bias. In contrast, attendance in the study III was more successful, as participation was optimized by scheduling study assessments during routine consultations. In epidemiology, we aim to match the source population with our target population. However, limitations due to self-selection in participation arise. Consequently, this can affect the results, as participants may be healthier and better using health care services, leading to less contrast between determinants and outcomes in our etiological analysis. We suspect that one explanation for the lack of a stepwise increase in the association between HRV and arterial stiffness across prediabetes and type 2 diabetes in study II is that the participants with type 2 diabetes represent a well-treated population. Thus, the included participants may be sufficient to demonstrate a relationship, the magnitude of the association to the target population may be limited.

6.1.3.2. Generalisability

The generalizability of our findings can be discussed on two levels: the extent to which the results apply to the general population within the country and how they translate

6.2. Discussion of results

to populations with different ancestries in other countries.

Studies II–III include individuals at high risk of diabetes and those with type 2 diabetes. Therefore, the associations between cardiovascular autonomic dysfunction and cardiovascular outcomes or surrogate biomarkers extend to individuals with some degree of diabetes risk. However, whether these associations hold in the general populations remains uncertain. Study I suggests that the link between autonomic dysfunction and cardiovascular risk, as measured by arterial stiffness, is also present in individuals with normal glucose metabolism, though to a lesser extent. This finding was further supported by replication in the Whitehall II cohort, strengthening the generalizability of the observed relationship²⁴.

The study populations in Studies II–III consist of individuals of Nordic descent, while Study I represents a population of Western European descent. Since the constellation of risk factors for diabetes varies and may manifest differently in population with Asian, South American, African, and other decent, and therefore our findings may not be fully generalizable to these groups. This limitation affects the applicability of the observed associations and their magnitudes to a unknown degree. Further cohort studies including under-represented populations are warranted. As we are studying diabetes risk, all participants in the study were older adults aged 40 years and above. Therefore, our findings are limited to this age group, and whether the results extend to younger adults or children remains to be confirmed. Overall, while our study has the strength of including individuals across different levels of diabetes risk, some limitations in generalizability remain, particularly to more diverse and younger populations.

6.2. Discussion of results

The challenges of population of type 2 diabetes and the risk of developing diabetes are addressed at multiple levels within the healthcare system.

- Public health focuses on preventing diabetes and its complications across all age groups, from childhood to older adulthood.
- Primary care, especially general practitioners, plays a central role in identifying individuals at risk of diabetes and cardiovascular disease. General practitioners also manage patients with uncomplicated type 2 diabetes.
- Outpatient clinics, led by endocrinologists, are responsible for treating patients with more advanced stages of diabetes and for managing complex cases.

6. Discussion [needs to be fine-tuned]

The aim of this thesis is to understand how cardiovascular autonomic dysfunction and CAN affects the risk of cardiovascular disease across stage of glucose metabolism. We included conditions such as heart failure, stroke, and myocardial infarction, as well as subclinical markers like carotid-femoral pulse wave velocity and carotid artery distensibility. The thesis includes populations across from normal glucose metabolism to type 2 diabetes and considers individuals engaged at different levels of the healthcare system. This chapter discusses the results and conclusions in relation to existing evidence and addresses their clinical implications across the levels of the health care system.

To address this aim, we used three different cohorts that reflect various levels of prevention and care. In Study I, we approached the question from a public health perspective by using data from The Maastricht Study including individuals aged 40 and above, representing all stages from normal glucose metabolism to type 2 diabetes. In this broader population, we demonstrated a link between lower 24-hour heart rate variability and cardiovascular risk, measured by arterial stiffness. This association was modified by glucose metabolism, showing a stronger relationship in individuals with prediabetes and type 2 diabetes.

This led to a focus on individuals at higher risk of developing diabetes, using data from the ADDITION-PRO cohort. Individuals with prediabetes may benefit from structured guidance in primary care to prevent progression to type 2 diabetes and related complications. In study II, we showed lower multiday HRV was linked to higher risk of CVD, heart failure and all-cause mortality.

A key challenge in managing type 2 diabetes lies in the complexity of clinical decision-making, which is often applied uniformly across a heterogeneous patient population. As the duration of diabetes increases, the disease typically progresses, leading to a higher prevalence of both microvascular and macrovascular complications. This raises the need to early identify subgroups of individuals who may benefit from more structured and personalized treatment strategies based on their risk profile. However, to support such an approach, reliable and standardized tools are required to accurately detect and classify high-risk phenotypes. To uncover this perspective, we collected data for the CANCAN study, which included individuals with type 2 diabetes who were referred to secondary care at an outpatient clinic by general practitioners. In this study (study III), we showed among individuals with type 2 diabetes that those with CAN had higher heart failure risk, measured by elevated NT-proBNP levels, and this association remained significant in subgroups without heart failure symptoms.

Cardiovascular autonomic dysfunction, indicated by lower HRV or abnormal values in CARTs, is linked with cardiovascular risk across all stage of glucose metabolism. In the next section we will discuss potential mechanism and explore the utility of HRV and CART in different stages of diabetes risk.

6.2.1. Cardiovascular autonomic dysfunction impact on heart disease across glucose metabolism

Based on our studies, we have shown that cardiovascular autonomic dysfunction, measured by HRV and CART, is associated with CVD risk glucose metabolism by measures of arteriosclerosis, atherosclerosis events, all-cause mortality, and heart failure in people at high risk of diabetes, as well as indications of heart failure in patients with type 2 diabetes.

6.2.1.1. Arteriosclerosis

In Study II, we demonstrated that autonomic dysfunction, as measured by 24-hour HRV, is associated with arterial stiffness measured both dynamically (pulse wave velocity) and locally (carotid distensibility). 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.

Two possible mechanisms might explain how autonomic nervous function is related to arterial stiffness. First, autonomic nervous dysfunction may increase the vascular tone of large arteries, thereby impairing arterial elasticity. Animal studies support this notion. In rats, proper autonomic regulation has been shown to be essential for maintaining aortic elasticity, and heightened sympathetic activity has been shown to damage elastin fibres, resulting in stiffer arteries. While such findings cannot be directly extrapolated to humans, they suggest plausible biological pathways. Second, the autonomic nervous system regulates heart rate and cardiac contractility. Autonomic dysfunction typically manifests as both reduced heart rate variability 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 arterial stiffness by altering blood flow dynamics and increasing shear stress. Our earlier study using data from the Whitehall II cohort showed that a steeper decrease in short-term (5min) HRV over a ten-year period was linked with higher levels of aortic stiffness in the subsequent five years²⁴.

Our data from Study I, extended this perspective by showing that the association between cardiovascular autonomic dysfunction and arterial stiffness is modified by dysglycemia, suggesting that the autonomic nervous system may lie on the pathway from dysglycemia to the development of arterial stiffness, even before the onset of type 2 diabetes. Data from Whitehall II showed how aortic stiffness have a steeper increase by higher HbA1c values among non-diabetic individuals²⁹. In the subpopulation in Study

6. Discussion [needs to be fine-tuned]

I without diabetes, we observed modification by HbA1c in both aortic and carotid stiffness. The modifying effect of diabetes status, suggest an amplified impact of hyperglycemia on the consequences of autonomic dysfunction. While several time-domain and frequency-domain HRV measures based on the global distribution were modified by diabetes status, the association of mean IBI was not. This suggests that the deterioration of HRV indicators may reflect a different pathogenesis of arterial stiffness in diabetes risk compared to heart rate.

6.2.1.2. Atherosclerosis

In Study II, we showed that individuals with a preclinical stage of autonomic dysfunction, measured by week-long HRV face a higher risk of incident ischemic-related cardiovascular disease, heart failure, and all-cause mortality.

Multiple mechanisms may explain how autonomic dysfunction contributes to the initiation and progression of ischemic events and stroke. First, as discussed in Study II, autonomic dysfunction may promote arteriosclerosis, leading to arterial stiffness. This stiffness impairs vasodilation and may enhance vasoconstriction, increasing hemodynamic stress and the risk of plaque rupture and thrombus formation³⁰. In this context, findings from Study II suggest that arterial stiffness is not entirely separate from atherosclerosis, which was been confirm by data from the Rotterdam Study³¹. As plaques develop, the associated increase in sympathetic nerve density around the arteries could reduce arterial elasticity. In a smaller study of people with type 2 diabetes, it was shown that lower HRV was linked with increase in carotid atherosclerosis³².

Second, the autonomic nervous system innervates the adventitia layer of blood vessels, where it modulates vascular tone via sympathetic fibers. 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 models³³. These findings suggest that autonomic dysfunction may not only reflect but also actively contribute to atherogenesis.

Third, the basis of autonomic nervous dysfunction has show to interfere with signalling pathway controlling the heart rhythm and thus lead to arrhythmias disturbing contraction of the heart. Data from the Atherosclerosis Risk In Communities study of illustrated that lower short-term HRV was associated with incident atrial fibrillation over 20 years, and the risk was higher among participants with type 2 diabetes³⁴. This supports autonomic dysfunctions role in the development of arrhythmogenesis which increase the risk

6.2. Discussion of results

of MI and stroke. However, in Study II, we do not have incident atrial fibrillation included as an outcome, therefore it would be needed to be explored to understand whether it could explain the higher risk of MACE. 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 a missing modulation of heart rate by parasympathetic response under stress may play a role in ischemia³⁵. In our week-long recordings, our data likely included episodes of stress-induced HRV under free-living circumstances, e.g. the first indication observed during the awakening stages in the morning. Hence, capturing autonomic responses to living circumstances and their alignment with the circadian rhythm may provide valuable information about cardiovascular risk. Therefore, understanding autonomic responses to tasks is relevant for comprehending their role in cardiovascular risk, beyond short-term measures taken at rest. Including data to monitor real-time activity, such as physical activity, would bring additional value to capture physiological responses to bodily demands. This could enable the inclusion of heart rate responses (e.g., from rest to standing) and other relevant measures of autonomic function, such as heart rate recovery after physical movement, which is a known risk factor for CVD and all-cause mortality [colechristopherr?].³⁶.

6.2.1.3. Heart failure

The relationship between cardiovascular autonomic dysfunction and heart failure is complex³⁷. On one hand, autonomic dysfunction may represent complication of that contributes to cardiac stress, sympathetic overactivation, and eventual heart failure. On the other, it may reflect the progression of cardiac remodeling and declining cardiac output. Our findings demonstrated the relationship between autonomic dysfunction and heart failure both cross-sectionally in population with type 2 diabetes and prospectively in people representing different tiers of risk of diabetes. However, our data are limited in determining the extent to which the relationship points toward one explanation or the other, as we lack baseline and follow-up measures of both heart failure and heart rate variability.

Findings from Study I confirmed the relationship between autonomic dysfunction and arterial stiffness. It is well known that arterial stiffness is linked to cardiac remodelling, as increased pulse wave velocity leads to an earlier return of the reflected pulse wave to the aorta, which increases cardiac afterload and reduces coronary perfusion pressure³⁸. Therefore, arterial stiffness may have an indirect effect on heart failure, potentially driven by autonomic dysfunction. However, structured analyses are needed to confirm these pathways, for example through mediation analysis to assess the direct and indirect effects of autonomic dysfunction. In study II, we observed that week-long HRV was linked with incident heart failure and a fourth of the risk was explained by resting heart rate.

6. Discussion [needs to be fine-tuned]

Data from the Rotterdam Study showed that short-term HRV was longitudinally associated with echocardiographic measures reflecting systolic function, suggesting autonomic dysfunction contributes to cardiac remodelling³⁹. In contrast to MACE outcomes, findings from Study II showed no specific time point in hourly HRV associated with heart failure. Instead, it was the overall daily pattern captured by week-long HRV that was linked to heart failure risk. This suggests that the association is not driven by isolated shifts in autonomic activity, but rather by a consistently impaired autonomic balance in 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 an increased risk of heart failure.

[Study III: NT-proBNP]

We cannot exclude the possibility that autonomic dysfunction represents an elevated demand for compensatory mechanisms as heart failure progresses. Studies have shown that patients with heart failure and lower HRV tend to have a worse prognosis of mortality. If low HRV or the presence of CAN were primarily driven by existing cardiac complications, it would suggest that individuals with these conditions exhibit more pronounced sympathetic overactivity as a consequence of heart failure progression, and thus reverse causation. Hence, elevated sympathetic activity during rest may indicate a greater reliance on compensatory mechanisms to maintain cardiac output. More precise measures are needed to assess sympathetic activity as primary driver of heart failure or secondary compensating mechanism of cardiac dysfunction. In addition, it remains unclear to what extent the parasympathetic nervous system can act as a protective mechanisms to counterbalance sympathetic dominance, and whether a decline in the balance of HRV reflects a breakdown. 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 changes. In turn, cardiac remodeling 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.

6.2.2. Clinical implications

- General practitioner
 - CAN in T2D for risk stratified solutions
- Endocrinologist

6.2. Discussion of results

- CAN in T2D for risk stratified solutions
- circadian rhythm in research and HRV + heart rate.

We have discussed the utility of different cohorts representing public health, primary care, and secondary care in addressing the impact of autonomic dysfunction on cardiovascular disease, as well as the possible mechanisms involved. We will now focus on the clinical implications of using autonomic dysfunction in the prevention of cardiovascular disease. If long-term HRV or CART is to be considered for improving risk stratification, it remains 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.

6.2.2.1. Public health

Previous studies have demonstrated associations between HRV and arterial stiffness in individuals with type 1 and type 2 diabetes⁴⁰. Building on this, our earlier work in the Whitehall II study showed that a steeper decline in HRV was linked to the development of arterial stiffness, even among individuals without type 2 diabetes²⁴. In Study II, we extended this perspective by examining a general population across the full spectrum of glucose metabolism. Our findings revealed that autonomic dysfunction, measured by long-term HRV, is consistently associated with arterial stiffness, regardless of glycemic status. In Study I, one SD lower HRV was equivalent to the effect of 2.7 additional years on pulse wave velocity and 1.6 years on carotid distensibility⁴¹. In Study II, long-term measures of HRV were strongly associated with cardiovascular risk, with an effect size equivalent to 4.5 additional years of aging for major adverse cardiovascular events and 2.2 to 2.4 years for heart failure per one SD (33 ms) lower in week-long SDNN intervals⁴². Autonomic dysfunction is known to precede the development of hypertension [43]⁴⁴, which is an early major risk factor for subsequent cardiovascular disease. Our results support the role of heart rate variability as a early marker of cardiovascular health, in the general population and among those with elevated cardiometabolic risk. As such, our studies suggest that monitoring CVD risk progression or remission through long-term HRV may be valuable.

A limitation of implementing HRV monitoring, especially for long-term recordings, has been the demanding equipment requirements, such as the need for ECG recorders like Holter monitors. In recent years, wearable devices have become increasingly popular among the general public⁴⁵. These devices offer an easy, non-invasive way to collect heart rate and HRV data and to monitor their progression over time. The next step is to ensure accurate measurement of interbeat intervals and to identify which HRV indices are most suitable as markers of cardiovascular health. In diabetes and cardiovascular research, 24-hour HRV measures of indices reflecting heart rate responses to in- and

6. Discussion [needs to be fine-tuned]

expiration such as RMSSD, HF and pNN50 are more sensitive to behavioral influences and therefore have not consistently shown strong associations with cardiovascular or metabolic outcomes, compared to measures based of total variability (SDNN, SDANN, TP, ULF, VLF, LF) [12]¹⁶.

If HRV monitoring proves effective by helping individuals maintain healthy, age-adjusted HRV through lifestyle changes, and by prompting healthcare use in response to sustained deterioration, then HRV could become a meaningful marker for long-term health monitoring. The challenge of wearable devices in health care is ensuring equitable access to this health service, as individuals from lower socioeconomic groups are less likely to own wearable devices. This raises the risk of health disparities by overlooking high-risk populations with lower income or education levels. Studies have shown that the majority of the general population is willing to share their health data with public health institutions and to allow algorithm-based systems, such as artificial intelligence, in collaboration with healthcare professionals, to monitor disease^{[45]46}. Therefore, monitoring HRV through wearable devices can serve as a first step in tracking health status and facilitating timely referrals to primary care when risk levels increase.

6.2.2.2. Primary care

As the clinical paradigm shifts from a focus on ischemia toward more preventive strategies targeting atherogenesis, greater attention is being paid to individual risk factors that predispose patients to plaque formation⁴⁷. Individuals with prediabetes live with an elevated cardiometabolic risk, which underscores the need for early and precise risk assessment⁴⁸. In this context, our findings support the integration of autonomic function assessment into routine cardiovascular risk stratification, particularly in patients with prediabetes or type 2 diabetes.

A central question that arises is whether autonomic dysfunction can serve not only as a potential marker of underlying pathophysiology but also as a clinically useful risk indicator for cardiovascular disease and heart failure. If so, it could help identify patients at higher risk and thereby improve risk stratification. This concept can be explored from two complementary perspectives. First, long-term measurements of HRV may enhance the precision of individual cardiovascular risk prediction when added to established clinical risk scores. Second, these measurements may help detect preclinical manifestations of cardiovascular autonomic dysfunction, which could be targeted to prevent future cardiovascular events.

This raises the question of whether incorporating long-term HRV into traditional cardiovascular risk models, such as the Systematic COronary Risk Evaluation 2 (SCORE-2) and the Framingham Risk Score, adds meaningful predictive value^{49,50}. While most

6.2. Discussion of results

biomarkers have shown limited incremental value beyond established predictors such as age, sex, lipid levels, diabetes status, and blood pressure, some studies suggest that 24-hour HRV may improve risk discrimination for cardiovascular disease and all-cause mortality in individuals with type 2 diabetes⁵¹, and for stroke in older adults⁵². However, a key limitation of these studies is that their reference models have not been calibrated or validated on a large scale cohorts, unlike SCORE2 and the Framingham Risk Score.

In parallel with these developments, the increasing availability of wearable devices capable of capturing long-term HRV data presents a practical opportunity for continuous monitoring in primary care settings. Wearable devices may facilitate earlier detection of autonomic dysfunction and support more personalized approaches to prevention and management. However, the clinical utility of stratifying patients based on preclinical autonomic dysfunction remains uncertain.

Importantly, these considerations are only actionable if interventions targeting autonomic function can be shown to reduce cardiovascular risk. In other words, patients with autonomic dysfunction must derive greater benefit from preventive strategies than those without. Emerging evidence suggests that both pharmacological and lifestyle interventions can improve HRV in the short term^{53,54}. For example, high-intensity interval training has been shown to improve autonomic function in obese individuals with and without type 2 diabetes, although benefits in HRV were observed only in those without diabetes⁵⁵. Similarly, lifestyle changes in individuals with prediabetes have been associated with improvements in short-term HRV, which may partly explain the reduction in diabetes risk independently of weight loss⁵⁶.

Nevertheless, it remains unclear whether these effects are sustainable over time and whether they translate into long-term cardiovascular protection. Particularly in the context of lifestyle improvements and intensified diabetes management, much of the observed enhancement in autonomic function may be mediated indirectly through improvements in cardiometabolic markers such as glucose levels, lipid profiles, body weight, maximal oxygen uptake, and blood pressure. Despite current uncertainties, monitoring autonomic function through long-term HRV may offer a valuable tool for assessing cardiovascular risk and tracking the impact of preventive strategies. However, its clinical utility must be confirmed through robust evidence demonstrating sustained effects and improved outcomes.

6.2.2.3. Secondary care

In Study III, we demonstrated promising results supporting the potential of using CART-based CAN screening to identify individuals with type 2 diabetes who may be living with asymptomatic heart failure.

6. Discussion [needs to be fine-tuned]

In Study III, we showed presence of CAN was linked with indicators of heart failure by elevated NT-proBNP, higher WATCH-DM risk score and presence of symptoms defined by NYHA. In subgroups without symptoms, defined as NYHA Class I, the association between CAN and elevated NT-proBNP remains. This supports the notion that CAN may help detect asymptomatic cases (ref.). [Discuss the challenge of assymptomatical HF]. Studies has shown that CAN is pronogstical linked with incident with heart failure and type 2 diabetes⁵⁷. This suggest regardless of the direction between CAN and indication of heart failure, the detection of CAN could be utilize to define individuals with heart failure risk. These individuals could be benefit from further cardiovascular assessment e.g. echocardiography or intervention on to prevent further progression of CAN. Heart failure risk is above 2 times higher people with type 2 diabetes compared to people without diabetes⁵⁸. In populations with type 2 diabetes, the risk of heart failure varies considerably, making reliable indicators for risk stratification important. Our findings support the notion of CAN as a useful marker to identify people with type 2 diabetes at higher risk of heart failure. However, further studies including measures from echocardiography are needed to validate this approach. If confirmed, this could open the door for targeted interventions based on risk stratification.

6.2.3. HRV implication in research

When using long-term HRV recordings, careful consideration is needed to determine how best to utilize the data in relation to the specific research objectives.

When HRV is analyzed in shorter segments (e.g., hourly or in 5-minute intervals), measures like RMSSD, pNN50, and HF appear to offer new insights into autonomic function and its relevance in diabetes and cardiovascular disease, e.g during night-time [⁵⁹]⁵³. SDANN and SDNNi aim to reduce the impact of short-term variability, such as that caused by physical activity, by calculating either the standard deviation of 5-minute segment mean IBI (SDANN) or the mean of standard deviations across 5-minute segments (SDNNi). [include lower-frequency points]. This helps smooth out transient fluctuations and better capture long-term autonomic modulation. Thus, behavioral patterns pose a limitation in physiological research aiming to disentangle the causal pathways between autonomic dysfunction and cardiovascular disease when using long-term HRV measures. These patterns likely introduce high variability between observations that is not attributable to autonomic function itself. However, it simultaneously highlights a potential target for intervention, given that low HRV may be indicative of adverse lifestyle patterns. For instance, behavioral patterns such as disrupted sleep or irregular meal timing may influence circadian fluctuations in HRV. Evidence from studies on night-shift workers suggests that meal timing affects HRV, with daytime meals leading to higher

6.2. Discussion of results

HRV during night hours⁵³. Thus, although long-term HRV may lack the precision to disentangle sympathetic and parasympathetic activity due to overlapping behavioral and physiological influences, it may be a valuable tool for assessing autonomic responses in free-living conditions and informing lifestyle-based strategies to improve cardiovascular health. Hence, HRV show potential as a responsive marker to monitor successfullness in CVD risk management.

Earlier studies have shown an association between autonomic dysfunction, as measured by short-term HRV during rest, and arterial stiffness⁴⁰[add cvd]. In Study I, we extended perspective of but long-term HRV, does link with arterial stiffness, suggesting autonomic response to free-living conditions contribute to the development of arterial stiffness. In addition, we found that HRV was associated with locally measured carotid distensibility. However, our results are limited by the inability to distinguish between sympathetic and parasympathetic contributions to arterial stiffness, or to determine whether the observed risk is driven by specific responses to living conditions or circadian rhythm variations.

As increased sympathetic nervous system activity has been linked to greater plaque formation, and may be modifiable by reducing sympathetic drive, the autonomic nervous system could play a role in reducing atherosclerotic thrombus formation. However, more physiological studies are needed to understand the mechanisms of atherosclerosis in the presence of autonomic nervous dysfunction, including the causal direction between the two, and how this interplay may be altered during the progression from normal glucose metabolism to type 2 diabetes. This requires more precise measures of both sympathetic and parasympathetic activity, as well as markers of endothelial dysfunction, beyond what is currently captured by HRV and common indices of arterial stiffness.

While GLP-1 receptor agonists are proven to lower cardiovascular risk, they have also been shown to increase heart rate and reduce HRV in short-term trials⁶⁰. This may seem conflicting with the hypothesis that reduced HRV reflects higher cardiovascular risk. However, the beneficial effects of GLP-1 agonists on cardiometabolic risk factors, including improved glycaemic control, weight loss, blood pressure reduction, and anti-inflammatory actions, likely outweigh the mild adverse effects on autonomic markers. Thus, the overall cardiovascular benefit is preserved despite small autonomic changes.

[[HRV is just a proxy for heart rate, controversy?] - HRV is just a proxy for heart rate - direct sympathetic activity at the location, but a proxy from heart rate signals.]

[A main limitation of our findings in terms of risk stratification is that we did not investigate, in metabolically at-risk populations, whether incorporating measures from long-term HRV or CART as individual risk factors or as components of a risk score improves risk detection by enhancing sensitivity or specificity compared to existing structured guidelines for screening, prevention, and treatment of CVD and heart failure.]

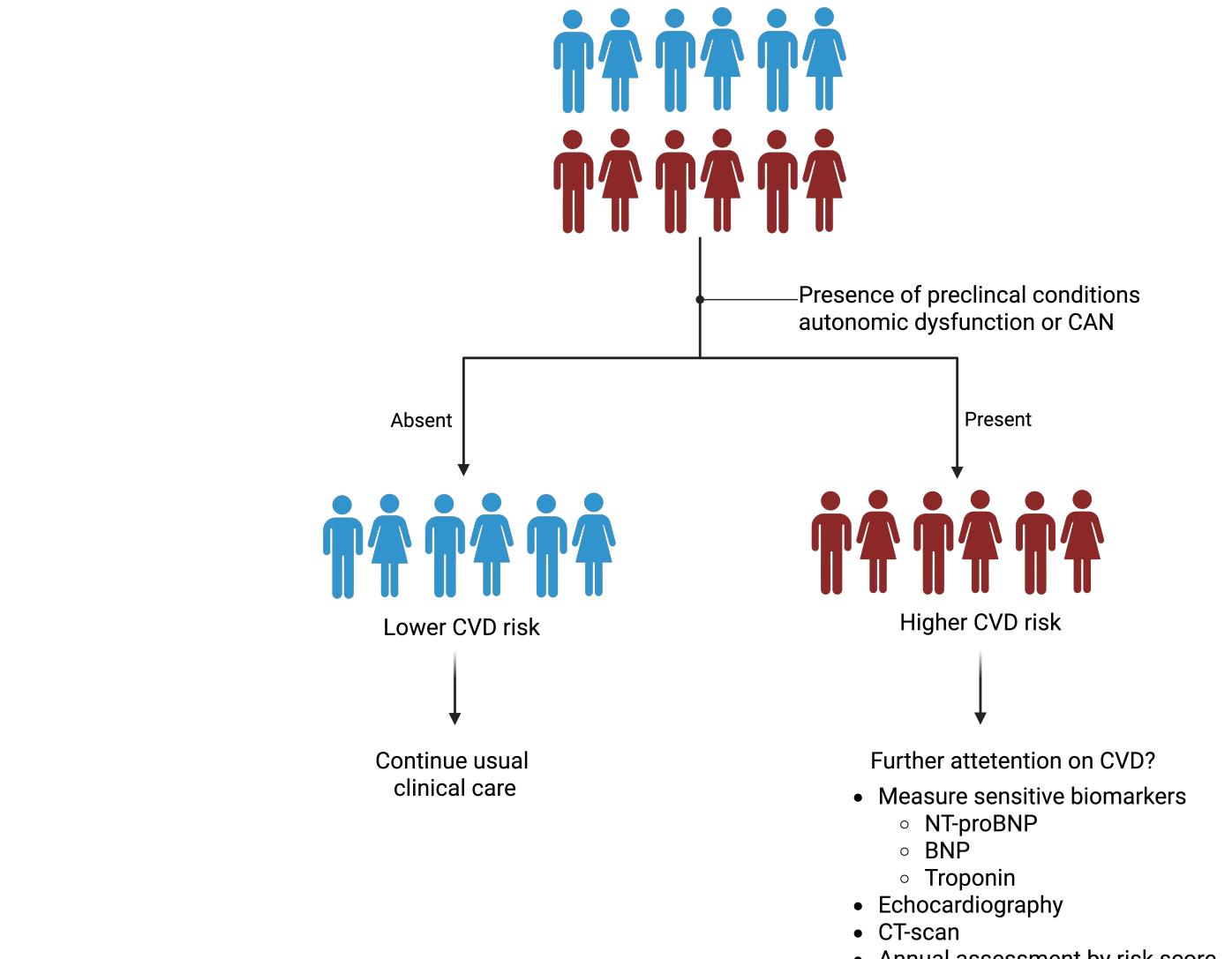
7. Perspective [needs to be fine-tuned]

7.1. Risk-stratification

Individuals with elevated glucose levels are at increased risk of developing metabolic complications and cardiovascular disease. However, many remain metabolically stable or even return to normal glucose regulation over time. As a result, structured treatment strategies for this group have not been widely adopted in clinical practice. This is partly due to the high degree of heterogeneity within this population. Therefore, additional indicators beyond glucose levels may be useful to identify those most likely to benefit from early intervention.

Our findings suggest that HRV may serve as a valuable marker for identifying individuals at elevated cardiovascular risk who could benefit from targeted preventive strategies. Future directions include evaluating whether individuals classified as high-risk based on autonomic dysfunction respond to specific interventions. However, a limitation of long-term HRV measurement is the lack of standardization, as data are collected under free-living conditions and may be influenced by daily behaviors, potentially affecting risk classification.

From a clinical perspective, CART has been shown to be reliable non-invasive and typically takes 8 to 10 minutes to complete. In Study III, we demonstrated a relationship between CAN and cardiac dysfunction, as measured by NT-proBNP. Despite . Heart failure is characterized by both structural and functional changes in the heart, such as left ventricular dysfunction, which can be assessed using echocardiography. However, the link between these structural and functional changes and their impact on systolic and diastolic pumping function in relation to CAN remains to be fully understood. Furthermore, the diagnostic and prognostic value of CAN, particularly its sensitivity and specificity in detecting HFrEF and HFpEF, requires further investigation.



7.2. Continuous monitoring of cardiovascular health

Over recent years, the use of wearable devices has increased in the general population⁴⁵, enabling comprehensive data collection on behavioral (e.g., sleep and physical activity) and physiological (e.g., heart rate, ECG, temperature) parameters⁶¹. These devices offer a broader and more feasible approach to long-term heart rate monitoring, requiring less equipment and user burden compared to traditional Holter monitors. Despite growing interest in wearable-based monitoring, the integration of HRV into routine cardiometabolic risk assessment remains limited.

Studies I and II demonstrated a strong association between long-term HRV and CVD risk, with particularly pronounced associations in individuals with prediabetes and type 2 diabetes. These findings suggest that HRV metrics could serve as early indicators for stratifying individuals who may benefit from preventive interventions. In the Whitehall II study, we further showed that a steeper 10-year decline in 5-minute HRV was associated with greater aortic stiffness development over the subsequent five years²⁴. Thus, a declining HRV trend detected by smartwatches may help identify individuals who require more intensive interventions.

In Study II, we also observed that specific morning time points were linked to CVD risk, suggesting that physiological responses captured under free-living conditions may provide valuable insights. Rather than adjusting for physical activity as a confounder, future predictive models could integrate multimodal data such as HRV, sleep, and activity patterns to capture dynamic physiological states and improve risk prediction. Incorporating HRV into digital health platforms may support personalized feedback loops, enabling timely lifestyle or therapeutic adjustments.

Hence, future studies can leverage wearable devices to continuously monitor risk by HRV and better understand the behavioral factors that contribute to its improvement or deterioration. This approach may help identify effective lifestyle patterns or medications that improve cardiovascular health through modulation of HRV.

However, standardization and transparency across different brands of wearable devices remain a challenge for both research and clinical implementation of heart rate and HRV monitoring. While smartwatches offer a convenient method for heart rate measurement, their accuracy can vary, as they rely on photoplethysmography to detect pulse rate at the wrist. This method can be imprecise under certain conditions, particularly during physical activity, due to motion artifacts and other external factors⁶². Despite these limitations, ongoing improvements in sensor technology and algorithm calibration are likely to enhance the reliability of wearable-derived heart rate and HRV data.

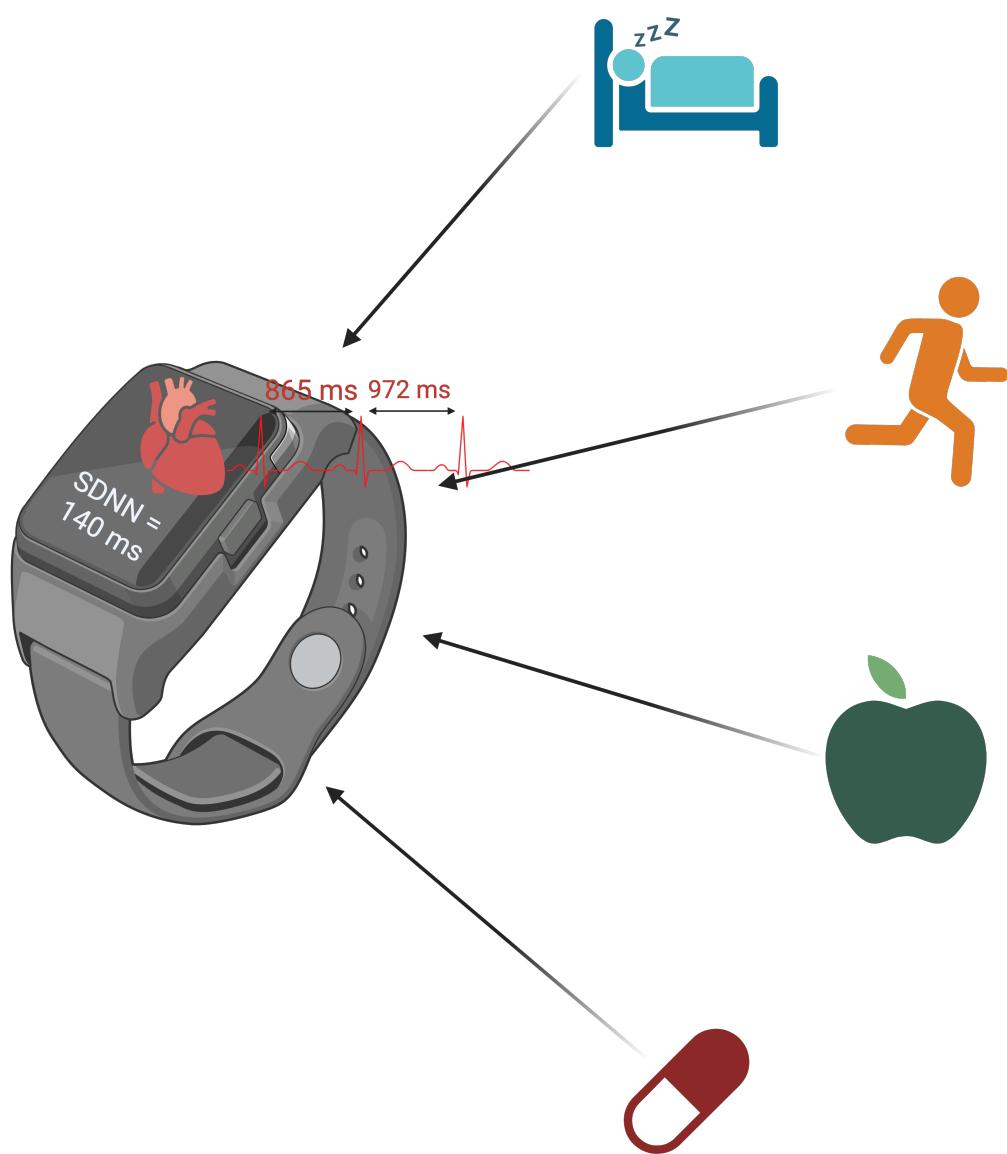


Figure 7.1.: Biofeedback HRV response to lifestyle and treatment solutions

7.3. Effective causal modifiable marker

Our findings in Studies I and II support the etiological link between long-term heart rate variability and the risk of cardiovascular disease, which provide a first line of evidence of a causal relationship. However, the observed association does not imply causation, and further research is necessary to determine whether the relationship between heart rate variability and cardiovascular disease risk is indeed causal. Traditionally, epidemiological research has relied on randomized controlled trials to establish causal relationships. However, conducting such trials to isolate the direct effect of heart rate variability is particularly challenging. Interventions that modify heart rate variability often do so indirectly, through changes in lifestyle factors such as weight loss, inflammation, or insulin sensitivity, or through pharmacological treatments like blood pressure medications. As a result, isolating the direct modification of heart rate variability is difficult. To address these limitations, modern epidemiological approaches such as Mendelian randomization (MR)⁶³ and structured causal mediation analysis offer promising alternatives for inferring causality from observational data [modern epidemiology 4th edition].

A genome-wide association study (GWAS) has identified 17 lead single nucleotide polymorphisms (SNPs) across eight loci associated with HRV based on short-term recordings, suggesting the potential for these variants to serve as genetic instruments in Mendelian randomization analyses⁶⁴. Another study demonstrated that phenotypically measured HRV was associated with all-cause mortality but found no evidence of a genetic association between genes linked to HRV and all-cause mortality⁶⁵. To date, no GWAS has been conducted to investigate the genetic determinants of long-term HRV. Establishing such genetic associations is essential for understanding its genetic architecture and for providing unconfounded estimates by using genetic variants as proxies to assess the causal role of HRV in cardiovascular disease.

A study has demonstrated that reduced HRV mediates the association between glomerular hyperfiltration and mortality⁶⁶, indicating an initial potential for HRV as a modifying factor. While this has been shown in observational data, no evidence of such mediation has yet been established in trial data. The Diabetes Prevention Program (DPP) showed that HRV may modify the effect of lifestyle intervention in preventing type 2 diabetes⁵⁶. However, it remains unclear to what extent this modification applies to cardiovascular outcomes, and whether the intervention was more effective among individuals with lower HRV. Cardiometabolic intervention trials, whether focused on lifestyle modification or pharmacological treatment, should, where feasible, include HRV measurements to enable structured mediation analyses and to better understand the role of autonomic function in cardiovascular outcomes. This could help demonstrate whether modification of HRV through potential strategies such as medications like beta-blockers or lifestyle interventions including physical activity, diet, and sleep has a sustainable effect on cardiovascular

7.3. Effective causal modifiable marker

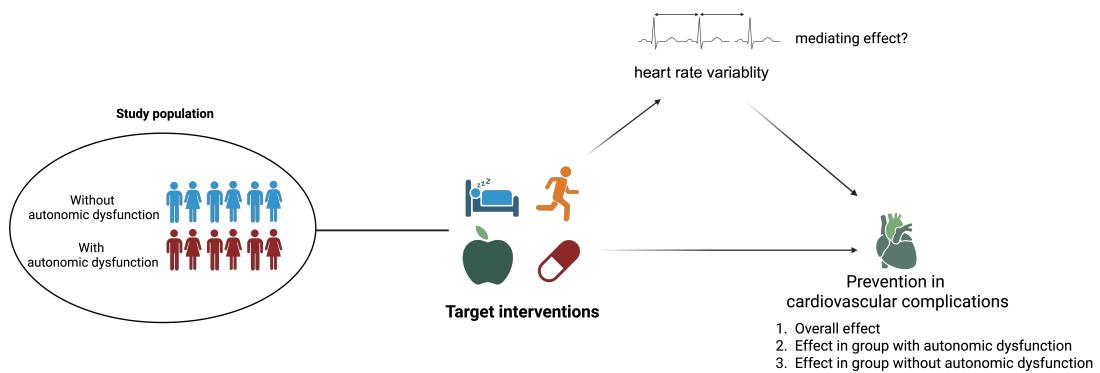


Figure 7.2.: Mediation of HRV by intervention in prevention of CVD

disease outcomes.

8. Conclusion [needs to be fine-tuned]

Autonomic dysfunction, assessed through 24-hour HRV, is associated with increased arterial stiffness. This relationship is already evident in individuals with normal glucose metabolism and becomes more pronounced in those with prediabetes and type 2 diabetes. In individuals at high risk of type 2 diabetes, lower long-term HRV measured over a week has been linked to ischemic events, heart failure, and all-cause mortality, highlighting HRV's potential as a marker of cardiovascular health. Both HRV and heart rate follow circadian patterns in relation to cardiovascular events. Higher nighttime heart rate is associated with increased risk of heart failure, and specific morning patterns of HRV have been linked to ischemic events. These findings suggest that both long-term and hourly HRV measures provide valuable prognostic information. Structured testing of cardiovascular autonomic function in individuals with type 2 diabetes can detect those with CAN and may help identify individuals at higher risk of heart failure.

We have established an association between HRV and cardiovascular complications. However, the underlying mechanism remains unclear. It is not yet known whether autonomic dysfunction, as indicated by low HRV, is a marker of developing arteriosclerosis, atheroma, or cardiac remodeling, or whether it plays a causal role in their development. While the pathogenic pathways leading to cardiovascular risk appear similar across the spectrum of glucose metabolism, dysglycemia may amplify the impact of autonomic dysfunction. Whether lower long-term HRV in individuals with prediabetes or type 2 diabetes reflects a distinct physiological mechanism involving neuropathy, compared to those with normal glucose metabolism, remains an open question.

Structured studies assessing screening strategies and trial designs, whether focused on lifestyle interventions or targeted pharmacological modulation of HRV, are needed to clarify the clinical role of HRV and CART in cardiovascular prevention. Long-term HRV and its hourly fluctuations provide insight into autonomic responses under free-living conditions. Further research is needed to determine whether modifying these measures can yield sustained preventive effects on cardiovascular disease and mortality. CARTs offer a standardized approach for diagnosing CAN. Clarifying the clinical utility of CARTs in assessing cardiovascular and heart failure risk through the identification of CAN is essential for advancing precision care in individuals with type 2 diabetes. Echocardiographic studies can help establish the link between CAN and the risk of specific heart failure

subtypes. Future research should carefully select HRV measures aligned with specific clinical or research objectives. Long-term HRV and CART have demonstrated potential in cardiovascular risk assessment and should be integrated to evaluate whether autonomic function assessments can monitor treatment or lifestyle effectiveness, or guide stratified cardiovascular risk decisions in individuals with prediabetes or type 2 diabetes.

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A. More results

Some results that wouldn't fit into the main thesis

B. Another appendix

Something else