KU LEUVEN

FACULTEIT INGENIEURSWETENSCHAPPEN

# Generation of 12-lead Synthetic ECG Signals

Pedro Devogelaere

Thesis submitted for the degree of
Master of Science in
Biomedical Engineering, option
Biomedical Data Analytics

**Thesis supervisor:**
Prof. dr. ir. Maarten De Vos

**Assessors:**
Prof. dr. Bert Vandenberk
Prof. dr. ir. Alexander Bertrand

**Mentor:**
Ir. L. Van Santvliet

Academic year 2024 – 2025

# Preface

I would like to thank everybody who kept me busy the last year, especially my promoter and my assistants. I would also like to thank the jury for reading the text. My sincere gratitude also goes to my wive and the rest of my family.

*Pedro Devogelaere*

# Contents

# Abstract

The `abstract` environment contains a more extensive overview of the work. But it should be limited to one page.

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

# List of Figures and Tables

## List of Figures



## List of Tables

# List of Abbreviations and Symbols

## Abbreviations

| | |
|---|---|
| LoG | Laplacian-of-Gaussian |
| MSE | Mean Square error |
| PSNR | Peak Signal-to-Noise ratio |

## Symbols

| | |
|---|---|
| 42 | "The Answer to the Ultimate Question of Life, the Universe, and Everything" according to |
| $c$ | Speed of light |
| $E$ | Energy |
| $m$ | Mass |
| $\pi$ | The number pi |

# Chapter 1

# Introduction

The first section contains a general introduction to the work. The goals are defined and the modus operandi is explained.

## 1.1 Electrocardiograms

The heart contains a dedicated conduction system that enables electrical signals to travel through it in a coordinated pattern. It consists of specialized elongated muscle cells connected by gap junctions, organized in conducting bundles such as the His bundle and Purkinje fibres, assuring good conductivity through the muscle [41]. Consequently, electrical impulses propagate through numerous fibres simultaneously and can thus be modelled as a surface of current dipoles. Since the human body acts as a volume conductor, this electrical activity can be measured as an electrocardiogram (ECG) between any two electrodes placed on the body, even though the voltage difference is small (at most four mV) [1, 31].
Specialized regions in the heart, known as nodes, are responsible for controlling this electrical system: these include the sinoatrial (SA) node and the atrioventricular (AV) node. Both nodes function as autonomous oscillators but can be modulated by the endocrine and nervous systems. The SA node serves as the heart's primary pacemaker. When the SA node fires, it generates an action potential (AP) that triggers a precise sequence of excitation and contraction events in the heart muscles. The order of these events is crucial for proper heart function, as illustrated in Figure 1.1, which shows the different phases of wave propagation through the heart and their correlation with a single-lead ECG [1, 31].

1. The SA node initiates the heartbeat by generating an action potential.

2. This signal spreads through the atria, causing them to depolarize and contract. On the ECG, this is represented as the P wave, which has a small amplitude (0.1–0.2 mV) and lasts about 60–80 ms due to the atria's slow contraction and small size.

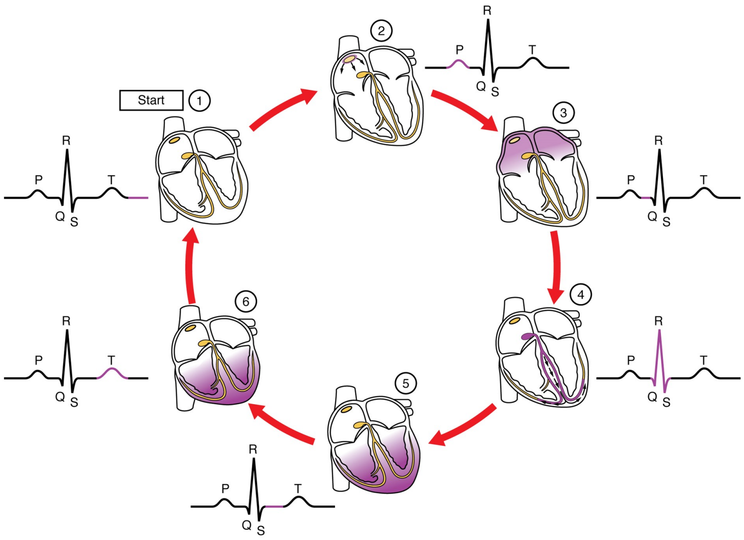


Figure 1.1: Different phases in the depolarization of the heart correlated with a single-lead ECG (lead II) and its typical waves [31]. The SA and AV nodes are indicated in yellow. The purple shading illustrates the propagation of the depolarizing wave through the heart. The purple segments in the ECG lead show which part of the electrical signal corresponds to each phase of cardiac depolarization.

3. After the P wave, the signal is delayed at the AV node, creating the PQ segment on the ECG. This is an iso-electric period lasting 60–80 ms.

4. The signal is then rapidly conducted through the His bundle, bundle branches, and Purkinje fibres to the ventricles. Ventricular depolarization begins at the apex and spreads upward, triggering ventricular contraction. This produces the QRS complex on the ECG, a sharp wave lasting approximately 80 ms with an amplitude of about 1 mV. The wave can be either biphasic or triphasic.

5. Following the QRS complex, another iso-electric phase occurs on the ECG spanning about 100–120 ms, called the ST segment. This interval reflects the extended action potential of ventricular cells, which lasts 300–350 ms.

6. Finally, the ventricles repolarize, resulting in the T wave. The T wave has an amplitude of 0.1–0.3 mV and spans 120–160 ms.

Some events like the repolarization of the atria, the firing of the SA node and Purkinje network propagation are too weak to be detected on the ECG because either not enough heart muscle cells are involved or extracellular current is generated [1, 27]. However, the human body's conductive properties are not homogeneous, as different tissues exhibit varying conductivities, while the presence of aligned fibres in muscles creates anisotropic conditions. To obtain comprehensive information about the heart's electrical activity, clinical practice uses a standardized 12-lead ECG system.

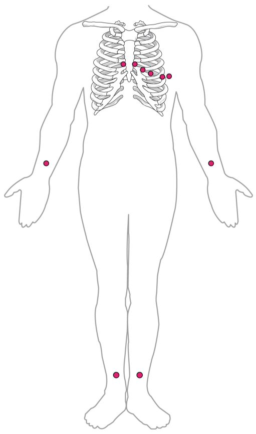

FIGURE 1.2: Standard electrode placement for a 12-lead electrocardiogram [31]

This system requires ten electrodes positioned at specific locations on the body with six electrodes placed on the chest and one on each limb, as illustrated in Figure 1.2, generating twelve different measurement channels called leads [1].

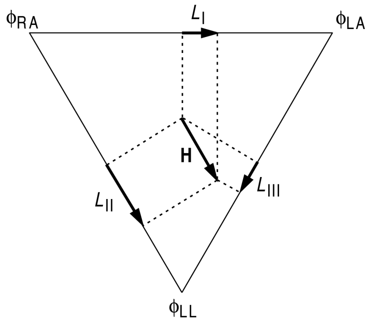


FIGURE 1.3: Einthoven's triangle showing a typical heart vector **H** and associated lead vectors [1]

Around the beginning of the twentieth century, Willem Einthoven established the first three leads, which are still used today [34]. By placing electrodes on the left arm (LA), right arm (RA), and left leg (LL), he could measure three different potential differences [1]:

$$\begin{aligned} I &= \phi_{LA} - \phi_{RA}, \\ II &= \phi_{LL} - \phi_{RA}, \\ III &= \phi_{LL} - \phi_{LA}. \end{aligned} \tag{1.1}$$

This configuration results in two independent equations and one dependent equation ($I + III = II$) from which information about the frontal plane can be retrieved. These three leads form an equilateral triangle, known as Einthoven's triangle, as illustrated in Figure 1.3 [26].

For the 12-lead ECG, three additional leads were introducedin the frontal plane by making linear combinations of the original limb leads. The formulas to derive leads aVR, aVL, and aVF from leads I and II are given by [26, 48, 39]:

$$\begin{bmatrix} aVR \\ aVL \\ aVF \end{bmatrix} = \begin{bmatrix} -\frac{1}{2} & -\frac{1}{2} \\ +1 & -\frac{1}{2} \\ -\frac{1}{2} & +1 \end{bmatrix} \begin{bmatrix} I \\ II \end{bmatrix}. \tag{1.2}$$

The six electrodes placed on the chest are used to define the six remaining leads giving information about the horizontal plane. In contrast to the limb leads, Wilson's Central Terminal is defined as a new 'zero reference'. This reference is calculated by averaging over leads $I, II$ and $III$, and is thus situated in the middle of Einthoven's triangle. The remaining leads are obtained by measuring the potential difference between the chest electrodes and Wilson's Central Terminal. By analyzing the limb leads and chest leads in conjunction, physicians can track the three-dimensional propagation of electrical signals through the heart. This detailed spatial information, combined with temporal ECG characteristics, allows for the detection of various cardiac abnormalities, making the ECG an essential tool in diagnosing heart conditions and assessing cardiac function [27].

Cardiac electrical activity is monitored in clinical practice through either short-term clinical ECG recordings or long-term Holter monitoring. The standard ten-minute ECG is conducted while patients remain at rest in a controlled clinical setting, providing a focused snapshot of cardiac function. In contrast, Holter monitoring tracks heart activity continuously over 24 hours or more as patients go about their daily routines, offering a more comprehensive view of cardiac behavior across different activities and conditions. While this extended monitoring period reduces patient and staff logistical burden compared to clinical ECG trials and can potentially detect heart conditions which do not appear frequently, recording during regular physical movement makes it more susceptible to movement artifacts and environmental noise that can affect data quality.

## 1.2 Generative Artificial Intelligence

Generative models are powerful tools used for tasks such as data augmentation, filling in missing data, protecting privacy, and benchmarking model performance. By creating high-quality synthetic data that closely resembles real data, these models make it possible to expand and diversify datasets in a safe way. This approach is well-established in image data, where it is easy to visually check if the generated samples look realistic. However, there is growing interest in using synthetic data for other types, including time series [29, 10, 45, 21], language processing [45, 24], and molecular structures [15, 33]. In these areas, ensuring authenticity is just as important but can be more difficult to evaluate.

A significant challenge in generative modelling is evaluating the synthetic data generated by these models. Various metrics have been proposed for this purpose, each providing different measures of data quality. At the distribution level, maximum mean discrepancy (MMD) assesses how well the underlying data distribution is learned by comparing sample statistics [10]. For signal-level comparison, several metrics are commonly employed: percentage root mean square difference (PRD) measures the distortion between real and generated signals, while root mean square error (RMSE) evaluates their stability [49]. Signal similarity can be assessed through the Fréchet distance (FD), where a lower value indicates higher quality, and through dynamic time warping (DTW), which has proven particularly effective for time series data [49, 9, 36]. Beyond these direct comparison metrics, evaluation can also be performed through classifier-based approaches. The synthetic-to-real (TSTR) method involves training a classifier on synthetic data and testing it on real data to assess whether the generative model produces samples suitable for replacing real data in applications. Conversely, the real-to-synthetic (TRTS) approach evaluates whether the model generates samples with realistic features [10].
The three main types of generative models are variational autoencoders (VAEs) [19], generative adversarial networks (GANs) [13], and diffusion models [38]. Each has unique strengths: VAEs are good at capturing continuous data distributions, GANs are known for producing high-quality images, and diffusion models are valued for creating stable and diverse samples across many data types [43]. The following section provides a detailed overview of these models.

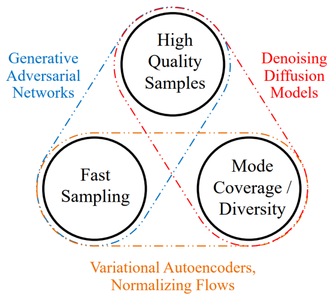


FIGURE 1.4: Comparison between generative artificial intelligence architectures [43]

### 1.2.1 Variational Autoencoders

Variational Autoencoders (VAEs) are a type of autoencoder that feature a unique structure enabling them to generate new, similar data samples. Like standard autoencoders, VAEs consist of two main parts: an encoder and a decoder. The encoder transforms observed data into latent (hidden) variables, which represent essential information in a compressed form (often referred to as the code). The decoder then takes these latent features and reconstructs them back into the original data space [19].
In [19], *Kingma et al.* introduced a probabilistic interpretation of autoencoders. VAEs

aim to learn the posterior distribution $p(\mathbf{z}|\mathbf{x})$, where $\mathbf{z}$ represents the latent variables and $\mathbf{x}$ denotes the observed data. However, the true posterior $p(\mathbf{z}|\mathbf{x})$ is intractable, so the encoder approximates it with a simpler distribution $q(\mathbf{z}|\mathbf{x})$, parameterized by $\phi$. This approximate distribution is referred to as a recognition model. The decoder then reconstructs data samples by mapping the latent features back to the data space using the likelihood $p(\mathbf{x}|\mathbf{z})$, parameterized by $\theta$ [19].
The objective of the VAE is to maximize the marginal likelihood of the observed data $p(\mathbf{x})$, but this is intractable to compute directly. Instead, *Kingma et al.* proposed a method to maximize a variational lower bound on this likelihood, known as the evidence lower bound (ELBO) [20]:

$$ELBO = \mathbb{E}_{q_\phi(\mathbf{z}|\mathbf{x})}\left[\log p_\theta(\mathbf{x} \mid \mathbf{z})\right] - \mathrm{KL}\left(q_\phi(\mathbf{z} \mid \mathbf{x}) \,\|\, p_\theta(\mathbf{z})\right). \tag{1.3}$$

This bound allows the model to optimize both the $\theta$ and $\phi$ parameters jointly, balancing reconstruction accuracy and the divergence between $q_\phi(\mathbf{z}|\mathbf{x})$ and the prior distribution $p_\theta(\mathbf{z})$. This approach enables VAEs to handle large datasets and approximate complex distributions, making them effective for tasks such as data generation and representation learning [20].

### 1.2.2 Generative Adversarial Networks

Generative Adversarial Networks (GANs) make use of two networks which try to beat each other in a minimax game. One of the networks, which is called the generator, tries to predict a data sample with noise as input, while the other, the discriminator, tries to differentiate between the real data samples and the generated data samples. This structure is reflected in the objective function [13]:

$$V(D,G) = \mathbb{E}_{\mathbf{x}\sim p_{\text{data}}(\mathbf{x})}\left[\log D(\mathbf{x})\right] + \mathbb{E}_{\mathbf{z}\sim p_{\mathbf{z}}(\mathbf{z})}\left[\log\left(1 - D(G(\mathbf{z}))\right)\right] \tag{1.4}$$

which has to be maximized with respect to the discriminator (D) and minimized with respect to the generator (G).
They have as an advantage high-quality samples and are cheap to sample from. However, a prominent problem of GANs is the variation in the samples which is often called the Helvetica scenario and corresponds to mode collapse. In this scenario, the generator finds a sample that works particularly well against the discriminator and starts only to output this sample [13].
*Arjovsky et al.* [4] propose a solution to this issue, where they substitute the discriminator which normally outputs a probability, with a critic (C) which outputs values on the real axis. Subsequently, the objective function is modified [4]:

$$\max_C \min_G \mathbb{E}_{\mathbf{x}\sim p_{\text{data}}(\mathbf{x})}\left[C(\mathbf{x})\right] - \mathbb{E}_{\mathbf{z}\sim p_{\mathbf{z}}(\mathbf{z})}\left[C(G(\mathbf{z}))\right] \tag{1.5}$$

which uses the Earth Mover distance, also known as the Wasserstein-1 distance.
GANs have often been used to generate realistic-looking images as in [32] where *Radford et al.* propose DCGAN. GANs have also shown promise for generating time series as described in [10, 29].

### 1.2.3 Diffusion Models

Diffusion models operate through two distinct processes: a forward diffusion process and its corresponding reverse process. During forward diffusion, the data undergoes stepwise degradation through the systematic addition of noise which is often Gaussian. Subsequently, the reverse process aims to reconstruct the original data by progressively removing this noise. This reconstruction is achieved through a neural network that learns to estimate the noise distribution parameters at each step. Specifically, for Gaussian noise the mean $\mu_\theta(\mathbf{x}_t, t)$ and variance $\sigma_\theta^2$ are estimated at each step, thereby enabling iterative noise removal and data restoration [38]. The objective function then becomes maximizing the lower bound on the log-likelihood as in VAEs [16]:

$$\mathbb{E}_q\left[\log p(\mathbf{x}_T) + \sum_{t\geq 1} \log \frac{p_\theta(\mathbf{x}_{t-1} \mid \mathbf{x}_t)}{q(\mathbf{x}_t \mid \mathbf{x}_{t-1})}\right] \tag{1.6}$$

*Ho et al.* [16] changed the objective from learning the mean of the data $\mu$, to learning the noise $\epsilon$ instead. The objective function to minimize becomes [16, 17]:

$$\mathbb{E}_{t,\mathbf{x}_0,\epsilon}\left[\left\|\epsilon - \epsilon_\theta\left(\mathbf{x}_t, t\right)\right\|^2\right]. \tag{1.7}$$

Diffusion models generate high-quality samples that are diverse and cover the full data distribution surpassing GANs in image generation [30]. However, due to their iterative nature with small step size, they are computationally expensive to sample [43].

## 1.3 Medical Time Series Generation

The generation of medical time series data using deep learning methods has evolved significantly over recent years. While initial approaches typically focused on generating univariate short segments, more recent methods have demonstrated increasing capability in producing complex multivariate signals. This section examines the key methodological developments in medical time series generation, with particular attention to their applications and limitations.

The application of GANs to medical time series generation was first systematically explored in 2017 by Esteban et al. [10]. Their approach employs recurrent neural networks (RNNs), specifically long short-term memory networks (LSTMs), for both the generator and discriminator components. They explored both conditional and non-conditional GAN variants. The generator uses as input a distinct noise sample for each time step of the series, with one conditional parameter in conditional setups. The discriminator assesses the authenticity of each sample point individually and also uses the conditional parameter in conditional setups.
Recognizing the challenges of evaluating medical time series generation, *Esteban et al.* proposed two evaluation frameworks: testing classification models trained on synthetic data against real data (TSTR) and vice versa (TRTS). These approaches

provide quantitative metrics for assessing generation quality without relying on costly expert reviews. To validate these methods, they utilized both synthetic datasets (sine waves and Gaussian processes) and real intensive care unit (ICU) data such as pulse oximeter, heart rate, respiratory rate, and mean arterial pressure signals. These vital measurements were originally recorded every five minutes and then down-sampled by a factor of three. The study focused on sixteen points corresponding to the initial four hours of a patient's stay.

In a following study, *Zhu et al.* [49] applied a GAN-based architecture to synthetic ECG generation but modified the previous LSTM setup. They replaced the LSTM in the generator with a bidirectional LSTM (BiLSTM), allowing it to consider both past and future values in the time series, and replaced the LSTM in the discriminator with a 1D convolutional network (CNN). CNNs, which are faster to train for long sequences, have shown promise in classification tasks for sequential data such as text and audio [23], [18], [47]. *Zhu et al.* specifically generated ECG signals between 50 to 400 data points at test-time (0.14s to 1.11s at 360Hz), while their training data consisted of ECGs of 3,120 samples (8.66s at 360Hz). This difference in training-test length is unique and commonly not done. They identified 250 points as optimal based on root mean square error (RMSE) and Fréchet distance (FD) evaluations. Their method, however, was restricted to single-lead ECGs and did not include a conditional framework. The study compared the performance of their GAN architecture with RNN and LSTM models in both autoencoder (AE) and variational autoencoder (VAE) frameworks, noting that the GAN converged more rapidly. Additionally, they tested the 1D-CNN discriminator against multi-layer perceptron (MLP), LSTM, and gated recurrent unit (GRU) based discriminators, finding that the 1D-CNN yielded improved convergence.

In a subsequent comparison, *Delaney et al.* [9] evaluated [10] and [49] GAN architectures, examining the impact of using a bidirectional LSTM in the generator and a CNN-based discriminator. They tested metrics such as maximum mean discrepancy (MMD) and dynamic time warping (DTW) and conducted preliminary assessments of privacy through a membership inference test.

In another early work, *Golany and Radinsky* [12] devised a method for generating 1-lead personalized ECGs with a GAN. The length of these signals is 216 samples at a sampling rate of 360 Hz. They tried to match the wave features (P, Q, R, S, T) by heuristically adding an MSE loss to the generator objective function. By first training a general GAN network and then further training on personalized data, they were able to obtain more patient-specific samples. They evaluated their approach by training a classifier and comparing the average Area Under Curve (AUC) to different approaches.

In [7], *Brophy et al.* take a different approach, generating 1-lead ECGs based on images via GANs. They transform the time series into an image format by using the amplitude as a grayscale value and ordering the data into a rectangular format. Because of using this image-based format, they can use proven concepts from GAN image generation, improving training stability. This enables them to generate sequences of 4096 data points at 5 kHZ.

In 2020, *Brophy* [5] was the first to extend the generation of ECGs to a multivariate 2-lead setup. He uses a GAN with an LSTM network in the generator and a 2D CNN as the discriminator. The signals generated are of length 187. He uses MMD and DTW to evaluate these signals, where DTW is generalized to a multivariate setting. To assess privacy risks he performs a membership inference attack.

*Kuznetsov et al.* [22] focus mainly on automatically an interpretable set of features encoded in the latent space of their VAE architecture. They note that these features can be further used in automatic diagnostic systems. This approach enables them to generate ECGs with 400 data points at a sample rate of 500 HZ. The encoder and decoder networks both use CNNs in parallel with MLPs where the outputs are concatenated and then put into other MLPs. To evaluate their approach they use MMD. They also evaluated the interpretability of their feature space by each time varying one of the features and looking at the generated samples.

*Golany et al.* propose in [11] a framework based on their previous work [12] and on [37] applied in the image domain, using an ECG simulator in the loss function of the generator of a GAN to synthesize ECGs with realistic morphology and characteristics. Similarly to [12], they use an additional MSE loss, but this time they use the simulator simulated samples to calculate it on. They call this modified loss the Euler loss. They still produce ECGs of 216 samples at 360 Hz. However, in this work, they use instead of their MLP in the generator and 1D CNN in the discriminator, 1D CNNs in both the generator and discriminator. For their evaluation they employ the same method as before, using a classifier and comparing Precision-Recall curves between relevant settings. Like this they show using the simulated samples as input like in [37], performs worse than including them in the loss function. They also compare their output visually with real examples.

*Wulan et al.* [42] designed three different models to generate synthetic ECG signals, which they claim are more realistic and can last up to 20 seconds. The first model is inspired by WaveNet [40], an autoregressive model initially developed for audio generation, chosen due to its suitability for producing long, sequential signals. However, the sequential nature of this model results in slower training and generation compared to parallel methods, such as GANs. To address this limitation, *Wulan et al.* also proposed two GAN-based models that offer faster generation times based on [32] and [14]. Both approaches use a transformation to another domain. One uses the short-time-Fourier transform (STFT) to get a 2D time-frequency representation of the signal. They call this model SpectroGAN. The other uses the Wavelet Transform (WT) to get a multiresolution analysis of the signal. They call this model WaveletGAN. Contrary to most of the previous works, they propose a conditional framework where they include three different conditions. They train their architectures sequentially on harder tasks through the design of datasets of each time higher complexity. To validate their models they use TSTR and TRTS. With these metrics, they concluded that WaveletGAN performed best out of the three models in terms of producing high-quality data and matching the data distribution. However, their model based on WaveNet can produce time series of arbitrary length.

*Dasgupta et al.* [8] pointed out that previous synthetic ECGs did not effectively capture physiological patterns found in real ECGs, such as the P wave, QRS complex, and T wave. They introduced an attention mechanism in the generator, alongside a bidirectional LSTM, to better learn the dependencies among these patterns. This adjustment enabled the generation of longer sequences (512 time steps, equivalent to 2.84s at 180Hz). To address training instability, they replaced the traditional GAN loss [13] with the Wasserstein loss introduced by *Arjovsky et al.* [4], where the discriminator produces a real-valued "score" rather than a probability. This approach stabilized training, particularly when using complex models in the generator, like attention blocks. However, like previous models, their approach only generated single-lead ECGs and did not incorporate a conditional framework. They compared their model to state-of-the-art approaches [49] as well as other generative frameworks (AE, VAE) and a traditional non-deep learning method [28]. Four evaluation metrics were used: Percentage Root Mean Square Difference (PRD), RMSE, FD, and DTW.

The first study to generate 12-lead ECGs was conducted by *Zhang and Babaeizadeh* [48]. They built on a prior model by *Zhu et al.* [49], modifying the generator architecture by replacing the 1D BiLSTM with a 2D version. The second dimension was used to capture the physiological and spatial correlations between the leads of the same recording. In the discriminator, they similarly used a 2D CNN instead of the original 1D version. They generated 8 out of the 12 leads and then completed the set by applying rules detailed in Section 1.1. For labelling consistency, they used the Philips DXL ECG algorithm, assigning one of four labels to each ECG: left ventricular hypertrophy (LVH), left bundle branch block (LBBB), acute myocardial infarction (ACUTMI), and Normal. In their approach, they used an unconditional setting, splitting their database by class and training a separate GAN for each label. Each signal was a time series of 800 ms centred around the QRS complex, sampled at 500 Hz.
To generate ECG signals, they used a unique technique, generating ECGs during training and applying plausibility criteria to ensure quality. The criteria required: (1) the MMD between generated and test ECGs to be less than 0.004, (2) an amplitude range exceeding 1.2 mV, (3) the signal's maximum not falling in the first or last 50 samples, and (4) at least 10 training epochs. For generating multiple ECGs, they proposed continuing training based on prior epochs for each new ECG. To produce a 10-second ECG, they concatenated the same generated segment, enabling the DXL algorithm to validate class labels and calculate a success rate.
To evaluate the synthetic data, they compared the statistical features of the generated ECGs to those of the training set. They also computed PRD and RMSE between the synthetic signals and both the training and test datasets, as well as between the

test and training datasets.

*Thambawita et al.* [39] were the first to generate extended ECG signals of up to 10 seconds in length for a 12-lead setup. They introduced a modified version of WaveGAN, called WaveGAN*, as well as a custom network featuring a 1D U-Net-based generator named Pulse2Pulse to produce 8 ECG channels, which could be expanded to 12 leads using standard formulas, as described in Section 1.1. To maintain consistency, only ECGs classified as normal by the MUSE 12SL (GE Healthcare) system were used for training, thereby avoiding a mix of healthy and pathological ECGs. They validated the quality of generated ECGs by examining heart rate, P wave, QRS complex, T wave, and underlying dependencies through statistical comparisons. Their findings showed that the Pulse2Pulse model outperformed WaveGAN* in both training efficiency and performance, as assessed by the fraction of ECGs classified as normal by MUSE. Similar to previous studies, no conditional framework was employed.

*Brophy et al.* [6] build further on their previous work [5]. In this study, they explore different loss functions for the GAN architecture while also increasing the number of data points to 500 at a sample rate of 100 Hz. They keep their model architecture the same. The model is implemented without conditional parameters. By introducing the DTW in the loss function of the discriminatory, they want to improve the stability while training. By using the same metrics as before they show that good results can be achieved without stability issues. They also compare their proposed model to an LSTM network and VAE for generating ECGs.

In [35], *Sang et al.* propose a conditional variational autoencoder (VAE) to generate 12-lead ECG signals that can be tailored to specific subject characteristics, such as age, sex, BMI, heart position, and orientation. They chose the VAE architecture due to its more interpretable latent space compared to GANs. The architecture they employed was inspired by the work of *Ozan et al.*, who developed a similar model for generating EEG signals. In addition to the conditional VAE, they also implemented an unconditional VAE model. To evaluate the performance of the unconditional VAE, they utilized MMD, comparing it between 1,000 randomly sampled real ECG signals and generated ECGs and also against the MMD results obtained in a prior study by *Kuznetsov et al.* [22]. The conditional VAE was used to explore the relationships between latent space variables, conditional labels, and generated results. This evaluation involved visualizing different leads for inspection and comparing them with clinical data.

To this point, no diffusion model-based architectures had been proposed. In 2023, *Alcaraz and Strodthoff* introduced a diffusion-based approach to generate 10-second, 12-lead ECGs [3]. Their architecture builds on DiffWave [21], replacing its dilated convolutional layers with Structured State Space Sequence Model (SSSM) blocks, known as S4 layers. For comparison with relevant state-of-the-art methods, they implemented conditional versions of both WaveGAN* and Pulse2Pulse from *Tham-*

*bawita et al.* [39], although the original source code for these networks was unavailable. *Alcaraz and Strodthoff* also attempted to adapt other existing models [44, 25, 35] to generate ECGs with 1000 samples at a rate of 100 Hz, but these models could not achieve the required length, even when downscaled to 250 time steps. For evaluation, they trained a classifier for TSTR and TRTS comparisons and performed a clinical Turing test to assess the realism of the synthetic data. Unlike most prior models, their approach utilized a conditional framework. Similar to *Sang et al.* [35], they explored the relationships in modifying the conditional input to the generated signals. Finally, they concluded their model improves on [39], but still could not compensate for real samples.

Concurrently *Adib et al.* [2] designed a model based on the improved DDPM [30]. To keep the architecture the same as in [30] they transform a 1-lead time-series into a 3-channel image. They compare this model across different hyperparameters and to a GAN-based model applied to the original 1D signal. With their approach they generate 256 data points at 4 Hz. To evaluate the models they use DTW, FD, MMD and a classification task to test authenticity where they look at the average precision and the AUC for the Precision-Recall Curve (PRC) and Receiver Operator Curve (ROC). From these tests, they concluded the GAN model performed better than the DDPM proposing the DDPM should be applied ideally to 1D data instead of artificial 2D data to make a fair comparison.

Following up on *Alcaraz and Strodthoff* [3], *Zama and Schwenker* introduced the DSAT-ECG model, a diffusion-based approach to generate 10-second, 12-lead ECGs using a State Space Augmented Transformer (SPADE) architecture [46]. Their model replaces the S4 layers with SPADE to handle the complex dependencies in ECG data. For comparison, *Zama and Schwenker* evaluated their model against baseline methods including SSSD-ECG [3], WaveGAN*, and Pulse2Pulse [35]. For quality evaluation, they used DTW and MMD and also performed an authenticity assessment like in [3]. *Zama and Schwenker* concluded that DSAT-ECG outperformed prior models like SSSD-ECG. Although DSAT-ECG does not fully replace real samples for classifier training, it has high fidelity, bringing ECG synthesis closer to clinical application standards. Future directions include exploring trainable variances and latent diffusion for improved speed and quality.

TABLE 1.1: Comparison of Approaches for Synthetic ECG Generation

| **Study** | **Archit.** | **Dataset** | **Cond.** | **Length (sample rate)** | **Leads** | **Metrics** | **Year** |
|---|---|---|---|---|---|---|---|
| Esteban et al. [10] | LSTM (G & D) | Philips eICU | Yes | 16 (1/15min) | 1 | MMD, TSTR, TRTS | 2017 |
| Zhu et al. [49] | BiLSTM (G) 1D CNN (D) | 3120-sample ECG | No | 50-400 (360Hz) | 1 | PRD, RMSE, FD | 2019 |
| Golany & Radinsky [12] | MLP (G) 1D CNN (D) | MIT-BIH | No | 216 (360Hz) | 1 | Classification | 2019 |
| Delaney et al. [9] | BiLSTM (G) CNN (D) | Eval. of Esteban (2017), Zhu (2019) | No | - | 1 | MMD, DTW, membership inference | 2019 |
| Brophy [5] | LSTM (G) 2D CNN (D) | MIT-BIH | No | 187 (/) | 2 | MMD, DTW, membership inference | 2020 |
| Kuznetsov et al. [22] | CNN & MLP (Enc & Dec) | LU Cardiography | No | 400 (500Hz) | 1 | MMD | 2020 |
| Golany et al. [11] | 1D CNN (G & D) | MIT-BIH | No | 216 (360Hz) | 1 | Classification | 2020 |
| Wulan et al. [42] | WaveNet [40], DCGAN [32] | MIT-BIH | Yes | 1440 (360Hz) 250 (360Hz) | 1 | TSTR, TRTS | 2020 |
| Dasgupta et al. [8] | BiLSTM + Attn. (G) (D) | ECG (P, QRS, T) | No | 512 (2.84s) | 1 | PRD, RMSE, FD, DTW | 2021 |
| Zhang et al. [48] | 2D BiLSTM (G) 2D CNN (D) | PTB-XL, CCDD, CSE, Chapman and private | No | 400 (500Hz) | 12 | PRD, RMSE | 2021 |
| Thambawita et al. [39] | U-Net (G) CNN (D) | 10s, 12-lead ECG, normal only | No | 10s | 12 | - | 2021 |
| Brophy et al. [6] | 2D LSTM (G) 2D CNN (D) | MIT-BIH | No | 500 (100Hz) | 2 | MMD, DTW, membership inference | 2021 |
| Sang et al. [35] | 2D CNN (Enc) 2D CNN (Dec) | UK Biobank | Yes | 400 (500Hz) | 12 | MMD | 2022 |
| Alcaraz & Strodthoff [3] | DDPM [30] | PTB-XL | Yes | 1000 (100Hz) | 12 | TSTR, TRTS, Turing | 2023 |
| Adib et al. [2] | DDPM [30] | MIT-BIH | No | 256 (64Hz) | 1 | MMD, FD, DTW, Classification | 2023 |
| Zama & Schwenker [?] | DDPM [30] | PTB-XL | Yes | 1000 (100Hz) | 12 | TSTR, TRTS, Turing | 2023 |

# Chapter 2

# Context and objectives

The second section contains a small summary of the context of the problem and the contributions made in the work.

# Chapter 3

# Methodology

A chapter is a logical unit. It normally starts with an introduction, which you are reading now. The last topic of the chapter holds the conclusion.

## 3.1 The First Topic of the Chapter

First comes the introduction to this topic.

Nunc velit. Nullam elit sapien, eleifend eu, commodo nec, semper sit amet, elit. Nulla lectus risus, condimentum ut, laoreet eget, viverra nec, odio. Proin lobortis. Curabitur dictum arcu vel wisi. Cras id nulla venenatis tortor congue ultrices. Pellentesque eget pede. Sed eleifend sagittis elit. Nam sed tellus sit amet lectus ullamcorper tristique. Mauris enim sem, tristique eu, accumsan at, scelerisque vulputate, neque. Quisque lacus. Donec et ipsum sit amet elit nonummy aliquet. Sed viverra nisl at sem. Nam diam. Mauris ut dolor. Curabitur ornare tortor cursus velit.

### 3.1.1 An item

Please don't abuse enumerations: short enumerations shouldn't use "`itemize`" or "`enumerate`" environments. So *never write*:

> The Eiffel tower has three floors:
>
> - the first one;
> - the second one;
> - the third one.

But write:

> The Eiffel tower has three floors: the first one, the second one, and the third one.

## 3.2 Evaluation metrics

Vivamus sit amet pede. Duis interdum, nunc eget rutrum dignissim, nisl diam luctus leo, et tincidunt velit nisl id tellus. In lorem tellus, aliquet vitae, porta in, aliquet sed, lectus. Phasellus sodales. Ut varius scelerisque erat. In vel nibh eu eros imperdiet rutrum. Donec ac odio nec neque vulputate suscipit. Nam nec magna. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Nullam porta, odio et sagittis iaculis, wisi neque fringilla sapien, vel commodo lorem lorem id elit. Ut sem lectus, scelerisque eget, placerat et, tincidunt scelerisque, ligula. Pellentesque non orci.

### 3.2.1 Another item

Morbi tincidunt posuere arcu. Cras venenatis est vitae dolor. Vivamus scelerisque semper mi. Donec ipsum arcu, consequat scelerisque, viverra id, dictum at, metus. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut pede sem, tempus ut, porttitor bibendum, molestie eu, elit. Suspendisse potenti. Sed id lectus sit amet purus faucibus vehicula. Praesent sed sem non dui pharetra interdum. Nam viverra ultrices magna.

Aenean laoreet aliquam orci. Nunc interdum elementum urna. Quisque erat. Nullam tempor neque. Maecenas velit nibh, scelerisque a, consequat ut, viverra in, enim. Duis magna. Donec odio neque, tristique et, tincidunt eu, rhoncus ac, nunc. Mauris malesuada malesuada elit. Etiam lacus mauris, pretium vel, blandit in, ultricies id, libero. Phasellus bibendum erat ut diam. In congue imperdiet lectus.

## 3.3 Conclusion

The final section of the chapter gives an overview of the important results of this chapter. This implies that the introductory chapter and the concluding chapter don't need a conclusion.

Nunc sed pede. Praesent vitae lectus. Praesent neque justo, vehicula eget, interdum id, facilisis et, nibh. Phasellus at purus et libero lacinia dictum. Fusce aliquet. Nulla eu ante placerat leo semper dictum. Mauris metus. Curabitur lobortis. Curabitur sollicitudin hendrerit nunc. Donec ultrices lacus id ipsum.

# Chapter 4

# Results

Vivamus adipiscing. Curabitur imperdiet tempus turpis. Vivamus sapien dolor, congue venenatis, euismod eget, porta rhoncus, magna. Proin condimentum pretium enim. Fusce fringilla, libero et venenatis facilisis, eros enim cursus arcu, vitae facilisis odio augue vitae orci. Aliquam varius nibh ut odio. Sed condimentum condimentum nunc. Pellentesque eget massa. Pellentesque quis mauris. Donec ut ligula ac pede pulvinar lobortis. Pellentesque euismod. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent elit. Ut laoreet ornare est. Phasellus gravida vulputate nulla. Donec sit amet arcu ut sem tempor malesuada. Praesent hendrerit augue in urna. Proin enim ante, ornare vel, consequat ut, blandit in, justo. Donec felis elit, dignissim sed, sagittis ut, ullamcorper a, nulla. Aenean pharetra vulputate odio.

## 4.1 The First Topic of this Chapter

Quisque enim. Proin velit neque, tristique eu, eleifend eget, vestibulum nec, lacus. Vivamus odio. Duis odio urna, vehicula in, elementum aliquam, aliquet laoreet, tellus. Sed velit. Sed vel mi ac elit aliquet interdum. Etiam sapien neque, convallis et, aliquet vel, auctor non, arcu. Aliquam suscipit aliquam lectus. Proin tincidunt magna sed wisi. Integer blandit lacus ut lorem. Sed luctus justo sed enim.

### 4.1.1 An item

A master's thesis is never an isolated work. This means that your text must contain references. On-line documents as well as books can be referenced.

## 4.2 Figures

Figures are used to add illustrations to the text. The Figure 4.1 shows the KU Leuven logo as an illustration.

Figure 4.1: The KU Leuven logo.

| | | |
|---|---|---|
| gnats | gram | $13.65 |
| | each | .01 |
| gnu | stuffed | 92.50 |
| emu | | 33.33 |
| armadillo | frozen | 8.99 |

Table 4.1: A table with the wrong layout.

| Item | | |
|---|---|---|
| Animal | Description | Price ($) |
| Gnat | per gram | 13.65 |
| | each | 0.01 |
| Gnu | stuffed | 92.50 |
| Emu | stuffed | 33.33 |
| Armadillo | frozen | 8.99 |

Table 4.2: A table with the correct layout.

## 4.3 Tables

Tables are used to present data neatly arranged. A table is normally not a spreadsheet! Compare Table 4.1 en Table 4.2: which table do you prefer?

## 4.4 Lorem Ipsum

This section is added to check headers and footers. So this chapter must at least contain three pages. To make sure that we get the required amount, the lipsum package isn't used but the text is put directly in the text.

### 4.4.1 Lorem ipsum dolor sit amet, consectetur adipiscing elit

Sed nec tortor id felis tristique sodales. Nulla nec massa eu dui fermentum tincidunt. Integer ullamcorper ante eget eros posuere faucibus. Nam id ligula ut augue pulvinar vulputate id at purus. Aenean condimentum tortor eu mi placerat eget eleifend massa mollis. Nam est mi, sagittis quis euismod eget, sagittis in nibh. Proin elit turpis, aliquam et imperdiet sed, volutpat eu turpis.

Pellentesque vel enim tellus, vitae egestas turpis. Praesent malesuada elit non nisi sollicitudin non blandit lacus tincidunt. Morbi blandit urna at lectus ornare laoreet. Suspendisse turpis diam, lobortis dictum luctus quis, commodo at lorem. Integer lacinia convallis ultricies. Sed quis augue neque, eu malesuada arcu. Nullam vehicula, purus vitae sagittis pulvinar, erat eros semper massa, eu egestas nibh erat quis magna. Cras pellentesque, nisl eu dapibus volutpat, urna augue ornare quam, quis egestas lectus nulla a lectus.

Vivamus dictum libero in massa cursus sed vulputate eros imperdiet. Donec lacinia, libero ac lobortis egestas, nibh dui ornare arcu, luctus porttitor velit massa sit amet quam. Maecenas scelerisque laoreet diam, vitae congue quam adipiscing vitae. Aliquam cursus nisl a leo convallis eleifend fermentum massa porta. Nunc libero quam, dapibus dapibus molestie sit amet, faucibus vel nunc.

### 4.4.2 Praesent auctor venenatis posuere

Sed tellus augue, molestie in pulvinar lacinia, dapibus non ipsum. Fusce vitae mi vitae enim ullamcorper hendrerit eu malesuada est. Proin iaculis ante sed nibh tincidunt vel interdum libero posuere. Vivamus accumsan metus quis felis congue suscipit dapibus enim mattis. Fusce mattis tortor eget ipsum interdum sagittis auctor id metus.

Integer diam lacus, pharetra sit amet tempor et, tristique non lorem. Aenean auctor, nisi eu interdum fermentum, lectus massa adipiscing elit, sed facilisis orci odio a lectus. Proin mi nibh, tempus quis porta a, viverra quis enim. In sollicitudin egestas libero, quis viverra velit molestie eget. Nulla rhoncus, dolor a mollis vestibulum, lacus elit semper nisi, nec sollicitudin sem urna eu magna. Nunc sed est urna, euismod congue mi.

### 4.4.3 Cras vulputate ultricies venenatis

Vivamus eros urna, sodales accumsan semper vel, lobortis sit amet mauris. Etiam condimentum eleifend lorem, ullamcorper ornare lectus aliquet vitae. Praesent massa enim, interdum sit amet semper et, venenatis ut elit. Quisque faucibus, quam ac lacinia imperdiet, nulla neque elementum purus, tempus rutrum justo massa porta sapien. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Sed ultrices interdum mi, et rhoncus sapien rutrum sed.

Duis elit orci, molestie quis sollicitudin sed, convallis non ante. Maecenas tincidunt condimentum justo, et ultricies leo tristique vitae. Vestibulum quis quam non lectus dapibus eleifend a vitae nibh. Nam nibh justo, pharetra quis iaculis consequat, elementum quis justo. Etiam mollis lacinia lacus, nec sollicitudin urna lobortis ac. Nulla facilisi.

Proin placerat risus eleifend erat ultricies placerat. Etiam rutrum magna nec turpis euismod consectetur. Phasellus tortor odio, lacinia imperdiet condimentum sed, faucibus commodo erat. Phasellus sed felis id ante placerat ultrices. Aenean tempor justo in tortor volutpat eu auctor dolor mollis. Aenean sit amet risus urna. Morbi viverra vehicula cursus.

### 4.4.4 Donec nibh ante, consectetur et posuere id, tempus nec arcu

Curabitur a tellus aliquet ipsum pellentesque scelerisque. Etiam congue, risus et volutpat rutrum, est purus dapibus leo, non cursus metus felis eget ligula. Vivamus facilisis tristique turpis, ut pretium lectus luctus eleifend. Fusce magna sapien, ullamcorper vitae fringilla id, euismod quis ante.

Phasellus volutpat, nunc et pharetra semper, sem justo adipiscing mauris, id blandit magna quam et orci. Vestibulum a erat purus, ut molestie ante. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Proin turpis diam, consequat ut ullamcorper ut, consequat eu orci. Sed metus risus, fringilla nec interdum vel, interdum eu nunc. Suspendisse vel sapien orci.

### 4.4.5 Morbi et mauris tempus purus ornare vehicula

Mauris sit amet diam quam, eget luctus purus. Sed faucibus, risus semper eleifend iaculis, mi turpis bibendum nisl, quis cursus nibh nisl sit amet ipsum. Vestibulum tempor urna vitae mi auctor malesuada eget non ligula. Nullam convallis, diam vel ultrices auctor, eros eros egestas elit, sed accumsan arcu tortor eget leo. Vestibulum orci purus, porttitor in pharetra eget, tincidunt eget nisl. Nullam sit amet nulla dui, facilisis vestibulum dui.

Donec faucibus facilisis mauris ac cursus. Duis rhoncus quam sed nisi laoreet eu scelerisque massa tincidunt. Vivamus sit amet libero nec arcu imperdiet tempor quis non libero. Sed consequat dignissim justo. Phasellus ullamcorper, velit quis posuere vulputate, felis erat tincidunt mauris, at vestibulum justo lectus et turpis. Maecenas lacinia convallis euismod. Quisque egestas fermentum sapien eu dictum. Sed nec lacus in purus dictum consequat quis vel nisl. Fusce non urna sem. Curabitur eu diam vitae elit accumsan blandit. Nullam fermentum nunc et leo dictum laoreet. Donec semper varius velit vel fringilla. Vivamus eu orci nunc.

## 4.5 Conclusion

The final section of the chapter gives an overview of the important results of this chapter. This implies that the introductory chapter and the concluding chapter don't need a conclusion.

Nunc sed pede. Praesent vitae lectus. Praesent neque justo, vehicula eget, interdum id, facilisis et, nibh. Phasellus at purus et libero lacinia dictum. Fusce aliquet. Nulla eu ante placerat leo semper dictum. Mauris metus. Curabitur lobortis. Curabitur sollicitudin hendrerit nunc. Donec ultrices lacus id ipsum.

# Chapter 5

# Discussion

Morbi malesuada hendrerit dui. Nunc mauris leo, dapibus sit amet, vestibulum et, commodo id, est. Pellentesque purus. Pellentesque tristique, nunc ac pulvinar adipiscing, justo eros consequat lectus, sit amet posuere lectus neque vel augue. Cras consectetuer libero ac eros. Ut eget massa. Fusce sit amet enim eleifend sem dictum auctor. In eget risus luctus wisi convallis pulvinar. Vivamus sapien risus, tempor in, viverra in, aliquet pellentesque, eros. Aliquam euismod libero a sem.

## 5.1 The First Topic of this Chapter

### 5.1.1 Item 1

#### Sub-item 1

Nunc velit augue, scelerisque dignissim, lobortis et, aliquam in, risus. In eu eros. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Curabitur vulputate elit viverra augue. Mauris fringilla, tortor sit amet malesuada mollis, sapien mi dapibus odio, ac imperdiet ligula enim eget nisl. Quisque vitae pede a pede aliquet suscipit. Phasellus tellus pede, viverra vestibulum, gravida id, laoreet in, justo. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Integer commodo luctus lectus. Mauris justo. Duis varius eros. Sed quam. Cras lacus eros, rutrum eget, varius quis, convallis iaculis, velit. Mauris imperdiet, metus at tristique venenatis, purus neque pellentesque mauris, a ultrices elit lacus nec tortor. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent malesuada. Nam lacus lectus, auctor sit amet, malesuada vel, elementum eget, metus. Duis neque pede, facilisis eget, egestas elementum, nonummy id, neque.

#### Sub-item 2

Proin non sem. Donec nec erat. Proin libero. Aliquam viverra arcu. Donec vitae purus. Donec felis mi, semper id, scelerisque porta, sollicitudin sed, turpis. Nulla in urna. Integer varius wisi non elit. Etiam nec sem. Mauris consequat, risus nec congue condimentum, ligula ligula suscipit urna, vitae porta odio erat quis sapien. Proin luctus leo id erat. Etiam massa metus, accumsan pellentesque, sagittis sit amet, venenatis nec, mauris. Praesent urna eros, ornare nec, vulputate eget, cursus sed, justo. Phasellus nec lorem. Nullam ligula ligula, mollis sit amet, faucibus vel, eleifend ac, dui. Aliquam erat volutpat.

### 5.1.2 Item 2

Fusce vehicula, tortor et gravida porttitor, metus nibh congue lorem, ut tempus purus mauris a pede. Integer tincidunt orci sit amet turpis. Aenean a metus. Aliquam vestibulum lobortis felis. Donec gravida. Sed sed urna. Mauris et orci. Integer ultrices feugiat ligula. Sed dignissim nibh a massa. Donec orci dui, tempor sed, tincidunt nonummy, viverra sit amet, turpis. Quisque lobortis. Proin venenatis tortor nec wisi. Vestibulum placerat. In hac habitasse platea dictumst. Aliquam porta mi quis risus. Donec sagittis luctus diam. Nam ipsum elit, imperdiet vitae, faucibus nec, fringilla eget, leo. Etiam quis dolor in sapien porttitor imperdiet.

## 5.2 The Second Topic

Cras pretium. Nulla malesuada ipsum ut libero. Suspendisse gravida hendrerit tellus. Maecenas quis lacus. Morbi fringilla. Vestibulum odio turpis, tempor vitae, scelerisque a, dictum non, massa. Praesent erat felis, porta sit amet, condimentum sit amet, placerat et, turpis. Praesent placerat lacus a enim. Vestibulum non eros. Ut congue. Donec tristique varius tortor. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Nam dictum dictum urna.

Phasellus vestibulum orci vel mauris. Fusce quam leo, adipiscing ac, pulvinar eget, molestie sit amet, erat. Sed diam. Suspendisse eros leo, tempus eget, dapibus sit amet, tempus eu, arcu. Vestibulum wisi metus, dapibus vel, luctus sit amet, condimentum quis, leo. Suspendisse molestie. Duis in ante. Ut sodales sem sit amet mauris. Suspendisse ornare pretium orci. Fusce tristique enim eget mi. Vestibulum eros elit, gravida ac, pharetra sed, lobortis in, massa. Proin at dolor. Duis accumsan accumsan pede. Nullam blandit elit in magna lacinia hendrerit. Ut nonummy luctus eros. Fusce eget tortor.

Ut sit amet magna. Cras a ligula eu urna dignissim viverra. Nullam tempor leo porta ipsum. Praesent purus. Nullam consequat. Mauris dictum sagittis dui. Vestibulum sollicitudin consectetuer wisi. In sit amet diam. Nullam malesuada pharetra risus. Proin lacus arcu, eleifend sed, vehicula at, congue sit amet, sem. Sed sagittis pede a nisl. Sed tincidunt odio a pede. Sed dui. Nam eu enim. Aliquam sagittis lacus eget libero. Pellentesque diam sem, sagittis molestie, tristique et, fermentum ornare, nibh. Nulla et tellus non felis imperdiet mattis. Aliquam erat volutpat.

## 5.3 Conclusion

Vestibulum sodales ipsum id augue. Integer ipsum pede, convallis sit amet, tristique vitae, tempor ut, nunc. Nam non ligula non lorem convallis hendrerit. Maecenas hendrerit. Sed magna odio, aliquam imperdiet, porta ac, aliquet eget, mi. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Vestibulum nisl sem, dignissim vel, euismod quis, egestas ut, orci. Nunc vitae risus vel metus euismod laoreet. Cras sit amet neque a turpis lobortis auctor. Sed aliquam sem ac elit. Cras velit lectus, facilisis id, dictum sed, porta rutrum, nisl. Nam hendrerit ipsum sed augue. Nullam scelerisque hendrerit wisi. Vivamus egestas arcu sed purus. Ut ornare lectus sed eros. Suspendisse potenti. Mauris sollicitudin pede vel velit. In hac habitasse platea dictumst.

Suspendisse erat mauris, nonummy eget, pretium eget, consequat vel, justo. Pellentesque consectetuer erat sed lacus. Nullam egestas nulla ac dui. Donec cursus rhoncus ipsum. Nunc et sem eu magna egestas malesuada. Vivamus dictum massa at dolor. Morbi est nulla, faucibus ac, posuere in, interdum ut, sapien. Proin consectetuer pretium urna. Donec sit amet nibh nec purus dignissim mattis. Phasellus vehicula elit at lacus. Nulla facilisi. Cras ut arcu. Sed consectetuer. Integer tristique elit quis felis consectetuer eleifend. Cras et lectus.

Ut congue malesuada justo. Curabitur congue, felis at hendrerit faucibus, mauris lacus porttitor pede, nec aliquam turpis diam feugiat arcu. Nullam rhoncus ipsum at risus. Vestibulum a dolor sed dolor fermentum vulputate. Sed nec ipsum dapibus urna bibendum lobortis. Vestibulum elit. Nam ligula arcu, volutpat eget, lacinia eu, lobortis ac, urna. Nam mollis ultrices nulla. Cras vulputate. Suspendisse at risus at metus pulvinar malesuada. Nullam lacus. Aliquam tempus magna. Aliquam ut purus. Proin tellus.

# Chapter 6

# Conclusion

The final chapter contains the overall conclusion. It also contains suggestions for future work and industrial applications.

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis. Donec nonummy pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

Quisque ullamcorper placerat ipsum. Cras nibh. Morbi vel justo vitae lacus tincidunt ultrices. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. In hac habitasse platea dictumst. Integer tempus convallis augue. Etiam facilisis. Nunc elementum fermentum wisi. Aenean placerat. Ut imperdiet, enim sed gravida sollicitudin, felis odio placerat quam, ac pulvinar elit purus eget enim. Nunc vitae tortor. Proin tempus nibh sit amet nisl. Vivamus quis tortor vitae risus porta vehicula.

Fusce mauris. Vestibulum luctus nibh at lectus. Sed bibendum, nulla a faucibus semper, leo velit ultricies tellus, ac venenatis arcu wisi vel nisl. Vestibulum diam. Aliquam pellentesque, augue quis sagittis posuere, turpis lacus congue quam, in hendrerit risus eros eget felis. Maecenas eget erat in sapien mattis porttitor. Vestibulum porttitor. Nulla facilisi. Sed a turpis eu lacus commodo facilisis. Morbi fringilla, wisi in dignissim interdum, justo lectus sagittis dui, et vehicula libero dui cursus dui. Mauris tempor ligula sed lacus. Duis cursus enim ut augue. Cras ac magna. Cras nulla. Nulla egestas. Curabitur a leo. Quisque egestas wisi eget nunc. Nam feugiat lacus vel est. Curabitur consectetuer.

Suspendisse vel felis. Ut lorem lorem, interdum eu, tincidunt sit amet, laoreet vitae, arcu. Aenean faucibus pede eu ante. Praesent enim elit, rutrum at, molestie non, nonummy vel, nisl. Ut lectus eros, malesuada sit amet, fermentum eu, sodales cursus, magna. Donec eu purus. Quisque vehicula, urna sed ultricies auctor, pede lorem egestas dui, et convallis elit erat sed nulla. Donec luctus. Curabitur et nunc. Aliquam dolor odio, commodo pretium, ultricies non, pharetra in, velit. Integer arcu est, nonummy in, fermentum faucibus, egestas vel, odio.

Sed commodo posuere pede. Mauris ut est. Ut quis purus. Sed ac odio. Sed vehicula hendrerit sem. Duis non odio. Morbi ut dui. Sed accumsan risus eget odio. In hac habitasse platea dictumst. Pellentesque non elit. Fusce sed justo eu urna porta tincidunt. Mauris felis odio, sollicitudin sed, volutpat a, ornare ac, erat. Morbi quis dolor. Donec pellentesque, erat ac sagittis semper, nunc dui lobortis purus, quis congue purus metus ultricies tellus. Proin et quam. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent sapien turpis, fermentum vel, eleifend faucibus, vehicula eu, lacus.

# Appendices

# Appendix A

# The First Appendix

Appendices hold useful data which is not essential to understand the work done in the master's thesis. An example is a (program) source. An appendix can also have sections as well as figures and references.

## A.1 More Lorem

Quisque facilisis auctor sapien. Pellentesque gravida hendrerit lectus. Mauris rutrum sodales sapien. Fusce hendrerit sem vel lorem. Integer pellentesque massa vel augue. Integer elit tortor, feugiat quis, sagittis et, ornare non, lacus. Vestibulum posuere pellentesque eros. Quisque venenatis ipsum dictum nulla. Aliquam quis quam non metus eleifend interdum. Nam eget sapien ac mauris malesuada adipiscing. Etiam eleifend neque sed quam. Nulla facilisi. Proin a ligula. Sed id dui eu nibh egestas tincidunt. Suspendisse arcu.

### A.1.1 Lorem 15–17

Nulla in ipsum. Praesent eros nulla, congue vitae, euismod ut, commodo a, wisi. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Aenean nonummy magna non leo. Sed felis erat, ullamcorper in, dictum non, ultricies ut, lectus. Proin vel arcu a odio lobortis euismod. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Proin ut est. Aliquam odio. Pellentesque massa turpis, cursus eu, euismod nec, tempor congue, nulla. Duis viverra gravida mauris. Cras tincidunt. Curabitur eros ligula, varius ut, pulvinar in, cursus faucibus, augue.

Nulla mattis luctus nulla. Duis commodo velit at leo. Aliquam vulputate magna et leo. Nam vestibulum ullamcorper leo. Vestibulum condimentum rutrum mauris. Donec id mauris. Morbi molestie justo et pede. Vivamus eget turpis sed nisl cursus tempor. Curabitur mollis sapien condimentum nunc. In wisi nisl, malesuada at, dignissim sit amet, lobortis in, odio. Aenean consequat arcu a ante. Pellentesque porta elit sit amet orci. Etiam at turpis nec elit ultricies imperdiet. Nulla facilisi.

In hac habitasse platea dictumst. Suspendisse viverra aliquam risus. Nullam pede justo, molestie nonummy, scelerisque eu, facilisis vel, arcu.

Curabitur tellus magna, porttitor a, commodo a, commodo in, tortor. Donec interdum. Praesent scelerisque. Maecenas posuere sodales odio. Vivamus metus lacus, varius quis, imperdiet quis, rhoncus a, turpis. Etiam ligula arcu, elementum a, venenatis quis, sollicitudin sed, metus. Donec nunc pede, tincidunt in, venenatis vitae, faucibus vel, nibh. Pellentesque wisi. Nullam malesuada. Morbi ut tellus ut pede tincidunt porta. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Etiam congue neque id dolor.

### A.1.2 Lorem 18–19

Donec et nisl at wisi luctus bibendum. Nam interdum tellus ac libero. Sed sem justo, laoreet vitae, fringilla at, adipiscing ut, nibh. Maecenas non sem quis tortor eleifend fermentum. Etiam id tortor ac mauris porta vulputate. Integer porta neque vitae massa. Maecenas tempus libero a libero posuere dictum. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Aenean quis mauris sed elit commodo placerat. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Vivamus rhoncus tincidunt libero. Etiam elementum pretium justo. Vivamus est. Morbi a tellus eget pede tristique commodo. Nulla nisl. Vestibulum sed nisl eu sapien cursus rutrum.

Nulla non mauris vitae wisi posuere convallis. Sed eu nulla nec eros scelerisque pharetra. Nullam varius. Etiam dignissim elementum metus. Vestibulum faucibus, metus sit amet mattis rhoncus, sapien dui laoreet odio, nec ultricies nibh augue a enim. Fusce in ligula. Quisque at magna et nulla commodo consequat. Proin accumsan imperdiet sem. Nunc porta. Donec feugiat mi at justo. Phasellus facilisis ipsum quis ante. In ac elit eget ipsum pharetra faucibus. Maecenas viverra nulla in massa.

## A.2 Lorem 51

Maecenas dui. Aliquam volutpat auctor lorem. Cras placerat est vitae lectus. Curabitur massa lectus, rutrum euismod, dignissim ut, dapibus a, odio. Ut eros erat, vulputate ut, interdum non, porta eu, erat. Cras fermentum, felis in porta congue, velit leo facilisis odio, vitae consectetuer lorem quam vitae orci. Sed ultrices, pede eu placerat auctor, ante ligula rutrum tellus, vel posuere nibh lacus nec nibh. Maecenas laoreet dolor at enim. Donec molestie dolor nec metus. Vestibulum libero. Sed quis erat. Sed tristique. Duis pede leo, fermentum quis, consectetuer eget, vulputate sit amet, erat.

# Appendix B

# The Last Appendix

Appendices are numbered with letters, but the sections and subsections use arabic numerals, as can be seen below.

## B.1 Lorem 20-24

Nulla ac nisl. Nullam urna nulla, ullamcorper in, interdum sit amet, gravida ut, risus. Aenean ac enim. In luctus. Phasellus eu quam vitae turpis viverra pellentesque. Duis feugiat felis ut enim. Phasellus pharetra, sem id porttitor sodales, magna nunc aliquet nibh, nec blandit nisl mauris at pede. Suspendisse risus risus, lobortis eget, semper at, imperdiet sit amet, quam. Quisque scelerisque dapibus nibh. Nam enim. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Nunc ut metus. Ut metus justo, auctor at, ultrices eu, sagittis ut, purus. Aliquam aliquam.

Etiam pede massa, dapibus vitae, rhoncus in, placerat posuere, odio. Vestibulum luctus commodo lacus. Morbi lacus dui, tempor sed, euismod eget, condimentum at, tortor. Phasellus aliquet odio ac lacus tempor faucibus. Praesent sed sem. Praesent iaculis. Cras rhoncus tellus sed justo ullamcorper sagittis. Donec quis orci. Sed ut tortor quis tellus euismod tincidunt. Suspendisse congue nisl eu elit. Aliquam tortor diam, tempus id, tristique eget, sodales vel, nulla. Praesent tellus mi, condimentum sed, viverra at, consectetuer quis, lectus. In auctor vehicula orci. Sed pede sapien, euismod in, suscipit in, pharetra placerat, metus. Vivamus commodo dui non odio. Donec et felis.

Etiam suscipit aliquam arcu. Aliquam sit amet est ac purus bibendum congue. Sed in eros. Morbi non orci. Pellentesque mattis lacinia elit. Fusce molestie velit in ligula. Nullam et orci vitae nibh vulputate auctor. Aliquam eget purus. Nulla auctor wisi sed ipsum. Morbi porttitor tellus ac enim. Fusce ornare. Proin ipsum enim, tincidunt in, ornare venenatis, molestie a, augue. Donec vel pede in lacus sagittis porta. Sed hendrerit ipsum quis nisl. Suspendisse quis massa ac nibh pretium cursus. Sed sodales. Nam eu neque quis pede dignissim ornare. Maecenas eu purus ac urna tincidunt congue.

Donec et nisl id sapien blandit mattis. Aenean dictum odio sit amet risus. Morbi purus. Nulla a est sit amet purus venenatis iaculis. Vivamus viverra purus vel magna. Donec in justo sed odio malesuada dapibus. Nunc ultrices aliquam nunc. Vivamus facilisis pellentesque velit. Nulla nunc velit, vulputate dapibus, vulputate id, mattis ac, justo. Nam mattis elit dapibus purus. Quisque enim risus, congue non, elementum ut, mattis quis, sem. Quisque elit.

Maecenas non massa. Vestibulum pharetra nulla at lorem. Duis quis quam id lacus dapibus interdum. Nulla lorem. Donec ut ante quis dolor bibendum condimentum. Etiam egestas tortor vitae lacus. Praesent cursus. Mauris bibendum pede at elit. Morbi et felis a lectus interdum facilisis. Sed suscipit gravida turpis. Nulla at lectus. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Praesent nonummy luctus nibh. Proin turpis nunc, congue eu, egestas ut, fringilla at, tellus. In hac habitasse platea dictumst.

## B.2 Lorem 25-27

Vivamus eu tellus sed tellus consequat suscipit. Nam orci orci, malesuada id, gravida nec, ultricies vitae, erat. Donec risus turpis, luctus sit amet, interdum quis, porta sed, ipsum. Suspendisse condimentum, tortor at egestas posuere, neque metus tempor orci, et tincidunt urna nunc a purus. Sed facilisis blandit tellus. Nunc risus sem, suscipit nec, eleifend quis, cursus quis, libero. Curabitur et dolor. Sed vitae sem. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Maecenas ante. Duis ullamcorper enim. Donec tristique enim eu leo. Nullam molestie elit eu dolor. Nullam bibendum, turpis vitae tristique gravida, quam sapien tempor lectus, quis pretium tellus purus ac quam. Nulla facilisi.

Duis aliquet dui in est. Donec eget est. Nunc lectus odio, varius at, fermentum in, accumsan non, enim. Aliquam erat volutpat. Proin sit amet nulla ut eros consectetuer cursus. Phasellus dapibus aliquam justo. Nunc laoreet. Donec consequat placerat magna. Duis pretium tincidunt justo. Sed sollicitudin vestibulum quam. Nam quis ligula. Vivamus at metus. Etiam imperdiet imperdiet pede. Aenean turpis. Fusce augue velit, scelerisque sollicitudin, dictum vitae, tempor et, pede. Donec wisi sapien, feugiat in, fermentum ut, sollicitudin adipiscing, metus.

Donec vel nibh ut felis consectetuer laoreet. Donec pede. Sed id quam id wisi laoreet suscipit. Nulla lectus dolor, aliquam ac, fringilla eget, mollis ut, orci. In pellentesque justo in ligula. Maecenas turpis. Donec eleifend leo at felis tincidunt consequat. Aenean turpis metus, malesuada sed, condimentum sit amet, auctor a, wisi. Pellentesque sapien elit, bibendum ac, posuere et, congue eu, felis. Vestibulum mattis libero quis metus scelerisque ultrices. Sed purus.

# Bibliography

[1] Cardiac Rhythmicity. In J. Keener and J. Sneyd, editors, *Mathematical Physiology*, pages 379–433. Springer, New York, NY, 1998.

[2] E. Adib, F. Afghah, and J. J. Prevost. Synthetic ECG Signal Generation Using Generative Neural Networks, Aug. 2022.

[3] J. M. L. Alcaraz and N. Strodthoff. Diffusion-based Conditional ECG Generation with Structured State Space Models, June 2023.

[4] M. Arjovsky, S. Chintala, and L. Bottou. Wasserstein GAN, Dec. 2017.

[5] E. Brophy. Synthesis of Dependent Multichannel ECG using Generative Adversarial Networks. In *Proceedings of the 29th ACM International Conference on Information & Knowledge Management*, CIKM '20, pages 3229–3232, New York, NY, USA, Oct. 2020. Association for Computing Machinery.

[6] E. Brophy, M. De Vos, G. Boylan, and T. Ward. Multivariate Generative Adversarial Networks and Their Loss Functions for Synthesis of Multichannel ECGs. *IEEE Access*, 9:158936–158945, Dec. 2021.

[7] E. Brophy, Z. Wang, and T. E. Ward. Quick and Easy Time Series Generation with Established Image-based GANs, Oct. 2019.

[8] S. Dasgupta, S. Das, and U. Bhattacharya. CardioGAN: An Attention-based Generative Adversarial Network for Generation of Electrocardiograms. In *2020 25th International Conference on Pattern Recognition (ICPR)*, pages 3193–3200, Jan. 2021.

[9] A. M. Delaney, E. Brophy, and T. E. Ward. Synthesis of Realistic ECG using Generative Adversarial Networks, Sept. 2019.

[10] C. Esteban, S. L. Hyland, and G. Rätsch. Real-valued (Medical) Time Series Generation with Recurrent Conditional GANs, Dec. 2017.

[11] T. Golany, D. Freedman, and K. Radinsky. SimGANs: Simulator-Based Generative Adversarial Networks for ECG Synthesis to Improve Deep ECG Classification, June 2020.

[12] T. Golany and K. Radinsky. PGANs: Personalized Generative Adversarial Networks for ECG Synthesis to Improve Patient-Specific Deep ECG Classification. *Proceedings of the AAAI Conference on Artificial Intelligence*, 33(01):557–564, July 2019.

[13] I. J. Goodfellow, J. Pouget-Abadie, M. Mirza, B. Xu, D. Warde-Farley, S. Ozair, A. Courville, and Y. Bengio. Generative Adversarial Networks, June 2014.

[14] I. Gulrajani, F. Ahmed, M. Arjovsky, V. Dumoulin, and A. Courville. Improved Training of Wasserstein GANs, Dec. 2017.

[15] A. Hawkins-Hooker, F. Depardieu, S. Baur, G. Couairon, A. Chen, and D. Bikard. Generating functional protein variants with variational autoencoders. *PLoS computational biology*, 17(2):e1008736, Feb. 2021.

[16] J. Ho, A. Jain, and P. Abbeel. Denoising Diffusion Probabilistic Models, Dec. 2020.

[17] A. Kazerouni, E. K. Aghdam, M. Heidari, R. Azad, M. Fayyaz, I. Hacihaliloglu, and D. Merhof. Diffusion Models for Medical Image Analysis: A Comprehensive Survey, June 2023.

[18] Y. Kim. Convolutional Neural Networks for Sentence Classification. In A. Moschitti, B. Pang, and W. Daelemans, editors, *Proceedings of the 2014 Conference on Empirical Methods in Natural Language Processing (EMNLP)*, pages 1746–1751, Doha, Qatar, Oct. 2014. Association for Computational Linguistics.

[19] D. P. Kingma and M. Welling. Auto-Encoding Variational Bayes, Dec. 2013.

[20] D. P. Kingma and M. Welling. An Introduction to Variational Autoencoders. *Foundations and Trends® in Machine Learning*, 12(4):307–392, 2019.

[21] Z. Kong, W. Ping, J. Huang, K. Zhao, and B. Catanzaro. DiffWave: A Versatile Diffusion Model for Audio Synthesis, Mar. 2021.

[22] V. V. Kuznetsov, V. A. Moskalenko, and N. Y. Zolotykh. Electrocardiogram Generation and Feature Extraction Using a Variational Autoencoder, Feb. 2020.

[23] Y. Lecun and Y. Bengio. Convolutional Networks for Images, Speech, and Time-Series. In *The Handbook of Brain Theory and Neural Networks*, Jan. 1995.

[24] J. Li, W. Monroe, T. Shi, S. Jean, A. Ritter, and D. Jurafsky. Adversarial Learning for Neural Dialogue Generation, Sept. 2017.

[25] X. Li, V. Metsis, H. Wang, and A. H. H. Ngu. TTS-GAN: A Transformer-based Time-Series Generative Adversarial Network, June 2022.

[26] A. Luna, V. Batchvarov, and M. Malik. The Morphology of the Electrocardiogram. Wiley-Blackwell, 2005.

[27] R. M. Rangayyan. Biomedical Signal Analysis: A Case-Study Approach. In *Biomedical Signal Analysis: A Case-Study Approach*, pages 14–28. Wiley-IEEE Press, 2002.

[28] P. McSharry, G. Clifford, L. Tarassenko, and L. Smith. A dynamical model for generating synthetic electrocardiogram signals. *IEEE Transactions on Biomedical Engineering*, 50(3):289–294, Mar. 2003.

[29] O. Mogren. C-RNN-GAN: Continuous recurrent neural networks with adversarial training, Nov. 2016.

[30] A. Nichol and P. Dhariwal. Improved Denoising Diffusion Probabilistic Models, Feb. 2021.

[31] OpenStax. The Cardiovascular System - The Heart. In *Anatomy and Physiology 2e*. OpenStax, Oct. 2022.

[32] A. Radford, L. Metz, and S. Chintala. Unsupervised Representation Learning with Deep Convolutional Generative Adversarial Networks, Jan. 2016.

[33] D. Repecka, V. Jauniskis, L. Karpus, E. Rembeza, I. Rokaitis, J. Zrimec, S. Poviloniene, A. Laurynenas, S. Viknander, W. Abuajwa, O. Savolainen, R. Meskys, M. K. M. Engqvist, and A. Zelezniak. Expanding functional protein sequence spaces using generative adversarial networks. *Nature Machine Intelligence*, 3(4):324–333, Apr. 2021.

[34] M. Rivera-Ruiz, C. Cajavilca, and J. Varon. Einthoven's String Galvanometer. *Texas Heart Institute Journal*, 35(2):174–178, 2008.

[35] Y. Sang, M. Beetz, and V. Grau. Generation of 12-Lead Electrocardiogram with Subject-Specific, Image-Derived Characteristics Using a Conditional Variational Autoencoder. In *2022 IEEE 19th International Symposium on Biomedical Imaging (ISBI)*, pages 1–5, Mar. 2022.

[36] J. Serrà and J. L. Arcos. An Empirical Evaluation of Similarity Measures for Time Series Classification, Jan. 2014.

[37] A. Shrivastava, T. Pfister, O. Tuzel, J. Susskind, W. Wang, and R. Webb. Learning from Simulated and Unsupervised Images through Adversarial Training, July 2017.

[38] J. Sohl-Dickstein, E. A. Weiss, N. Maheswaranathan, and S. Ganguli. Deep Unsupervised Learning using Nonequilibrium Thermodynamics, Nov. 2015.

[39] V. Thambawita, J. L. Isaksen, S. A. Hicks, J. Ghouse, G. Ahlberg, A. Linneberg, N. Grarup, C. Ellervik, M. S. Olesen, T. Hansen, C. Graff, N.-H. Holstein-Rathlou, I. Strümke, H. L. Hammer, M. M. Maleckar, P. Halvorsen, M. A. Riegler, and J. K. Kanters. DeepFake electrocardiograms using generative adversarial networks are the beginning of the end for privacy issues in medicine. *Scientific Reports*, 11(1):21896, Nov. 2021.

[40] A. van den Oord, S. Dieleman, H. Zen, K. Simonyan, O. Vinyals, A. Graves, N. Kalchbrenner, A. Senior, and K. Kavukcuoglu. WaveNet: A Generative Model for Raw Audio, Sept. 2016.

[41] F. Villanelo, Y. Escalona, C. Pareja-Barrueto, J. A. Garate, I. M. Skerrett, and T. Perez-Acle. Accessing gap-junction channel structure-function relationships through molecular modeling and simulations. *BMC Cell Biology*, 18(1):5, Jan. 2017.

[42] N. Wulan, W. Wang, P. Sun, K. Wang, Y. Xia, and H. Zhang. Generating electrocardiogram signals by deep learning. *Neurocomputing*, 404:122–136, Sept. 2020.

[43] Z. Xiao, K. Kreis, and A. Vahdat. Tackling the Generative Learning Trilemma with Denoising Diffusion GANs, Apr. 2022.

[44] J. Yoon, D. Jarrett, and M. van der Schaar. Time-series Generative Adversarial Networks. In *Advances in Neural Information Processing Systems*, volume 32. Curran Associates, Inc., 2019.

[45] L. Yu, W. Zhang, J. Wang, and Y. Yu. SeqGAN: Sequence Generative Adversarial Nets with Policy Gradient, Aug. 2017.

[46] M. H. Zama and F. Schwenker. ECG Synthesis via Diffusion-Based State Space Augmented Transformer. *Sensors*, 23(19):8328, Jan. 2023.

[47] X. Zhang, J. Zhao, and Y. LeCun. Character-level Convolutional Networks for Text Classification, Apr. 2016.

[48] Y.-H. Zhang and S. Babaeizadeh. Synthesis of standard 12-lead electrocardiograms using two dimensional generative adversarial network, June 2021.

[49] F. Zhu, F. Ye, Y. Fu, Q. Liu, and B. Shen. Electrocardiogram generation with a bidirectional LSTM-CNN generative adversarial network. *Scientific Reports*, 9(1):6734, May 2019.

# Master's thesis filing card

*Student*: Pedro Devogelaere

*Title*: Generation of 12-lead Synthetic ECG Signals

*UDC*: 621.3

*Abstract*:

Here comes a very short abstract, containing no more than 500 words. LaTeX commands can be used here. Blank lines (or the command `\par`) are not allowed!

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Thesis submitted for the degree of Master of Science in Biomedical Engineering, option Biomedical Data Analytics

*Thesis supervisor*: Prof. dr. ir. Maarten De Vos

*Assessors*: Prof. dr. Bert Vandenberk
Prof. dr. ir. Alexander Bertrand

*Mentor*: Ir. L. Van Santvliet