

Study on the use of convolutional neural networks for the diagnosis of atrial fibrillation

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Abstract – In this study we will introduce atrial fibrillation, one of the cardiac arrhythmias, and see how it can be diagnosed using convolutional neural networks in combination with various methods and supervised learning models, including: gray-level co-occurrence matrix, short-time Fourier transform based spectrogram, support-vector machines, k-nearest neighbors, multi-layer perceptron, focal loss, multi-scale decomposition, time-frequency analysis.

Index terms – Biomedical monitoring, electrocardiogram, arrhythmia, atrial fibrillation, deep learning, convolutional neural network, classification.

1. Introduction

Cardiovascular diseases are a group of diseases affecting the heart and/or blood vessels. On a world level, and in particular in countries with a typically Western lifestyle, cardiovascular diseases are the cause of 17 million deaths per year.

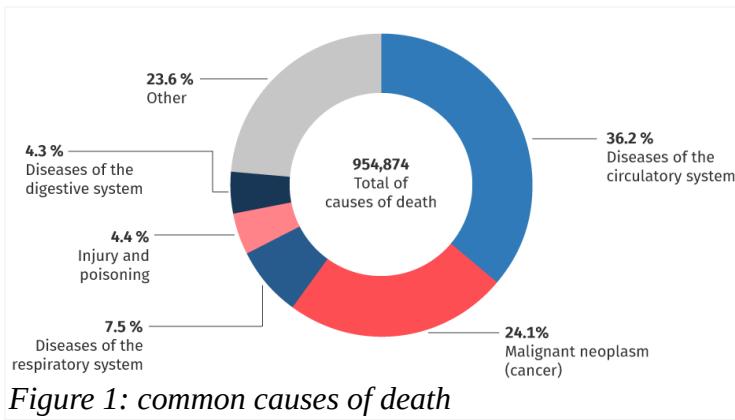


Figure 1: common causes of death

The narrowing, obstruction or excessive enlargement (aneurysm) of the blood vessels that can accompany this disease are in fact responsible for very widespread pathologies, such as coronary (angina pectoris and heart attack), cerebrovascular (stroke) and peripheral vascular diseases. In the family of cardiovascular pathologies, all congenital heart defects, rheumatic diseases involving myocardium, various forms of arrhythmia, pathologies affecting the heart valves and heart failure are also included. Cardiac pathologies are divided into: cardiovascular disease, coronary heart disease, heart "muscle" disease, heart valve disease, pericardial disease, heart conduction disease, vessel disease.

In this study we focus on heart conduction disease in particular on atrial fibrillation, one of the two arrhythmias^[b].

1.1. Electrocardiogram

The electrocardiogram (ECG) is the graphic reproduction of the electrical activity of the heart during its operation, recorded at the level of the body surface. On the surface of the body, low intensity electric fields (1mV) are present and can be recorded, which in the individual at rest are mainly due to periodic depolarizations and repolarizations of the heart. To record an electrocardiogram it is necessary to have electrodes placed on the body surface, forming leads arranged in such a way as to be able to better analyze the variations of the heart's dipole vector. In order to record the potentials, 10 electrodes are placed on the body: 4 peripheral (wrists and ankles) and 6 precordial, so as to record 12 leads.

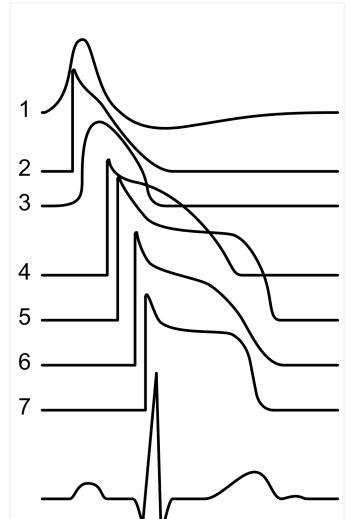


Figure 2: ECG related to the various action potentials of the heart

In general, the electrocardiogram (ECG) signals consist of six components that are designated as P, Q, R, S, T, and U:

- The P wave represents atrial depolarization [0.2 – 0.4mV];
- The QRS complex represents ventricular depolarization [1 – 2mV];
- The T wave represents ventricular repolarization [0.4 – 0.5mV];

- The U wave represents papillary muscle repolarization.

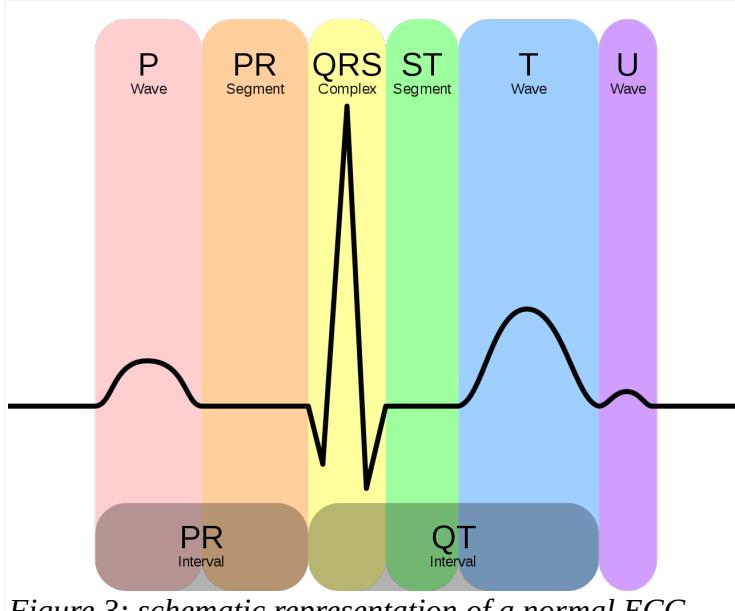


Figure 3: schematic representation of a normal ECG

Usually an electrocardiograph has an amplification of a factor of 60db only in the useful band. For monitoring it uses frequencies between 0.05 – 50Hz, while for diagnostics purpose it go up to 1kHz^[13].

1.2. Arrhythmia

Arrhythmia is a clinical condition in which the normal frequency or regularity of the heart rhythm is missing, or the physiological atrio-ventricular activation sequence is altered. Common symptoms are:

- Extrasystole: it is like a “void”, a missed beat;
- Tachycardia: the sensation is of an increase in beats, which can be regular but also irregular, fatigue, difficult breathing, dizziness;
- Bradycardia: fatigue, dizziness and possible loss of consciousness.

The alterations can have the following origins: at the level of the sinoatrial node, of supraventricular origin, at the level of the atrioventricular node, of ventricular origin. As for the supraventricular and ventricular origins, we have two types of fibrillation: atrial and ventricular^[c].

a) Ventricular fibrillation

Ventricular fibrillation (VF) is a very rapid, chaotic cardiac arrhythmia that causes uncoordinated contractions of the heart muscle. With the onset of this arrhythmia, blood circulation slows down considerably, up to cardio-circulatory arrest and subsequent respiratory arrest, until death if cardioversion of the rhythm is not intervened through defibrillation and cardiopulmonary resuscitation^[c].

b) Atrial fibrillation

Atrial fibrillation (AF) is a cardiac arrhythmia that originates in the atria. The electrical impulses that give rise to the contraction of the atria are activated in a totally chaotic and fragmentary way, giving rise to multiple wave fronts and disorganized and fragmentary contractions. The current clinical approach aims to treat symptoms by:

- rhythm control (i.e. recovery and maintenance of sinus rhythm with anti-arrhythmic drugs or catheter ablation);
- heart rate control with drugs that regulate the conduction of atrial stimuli to the ventricles associated with anti-thrombotic therapy.

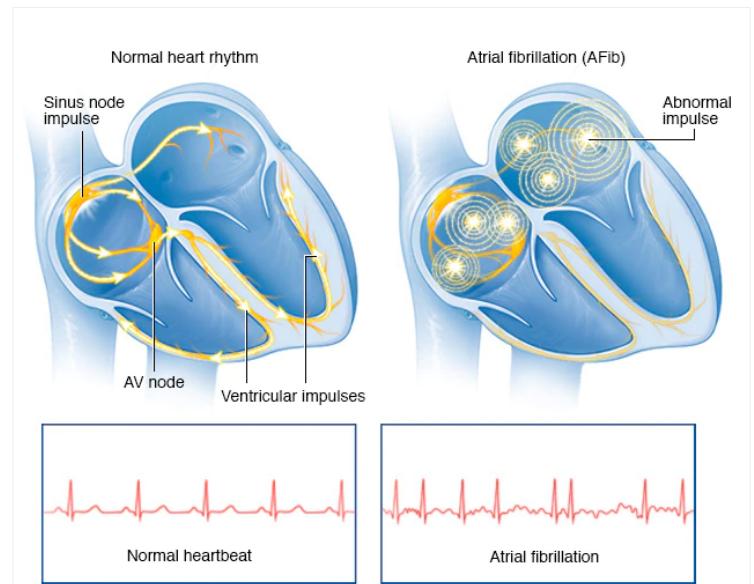


Figure 4: normal heartbeat & atrial fibrillation

From Figure 5 it can be observed that for AF patient there are tiny irregular fluctuations in the P-wave and QRS complex. Given the presence of these irregularities, for the purpose of arrhythmia screening various morphological features, including the peaks and widths corresponding to different ECG segments are typically used.

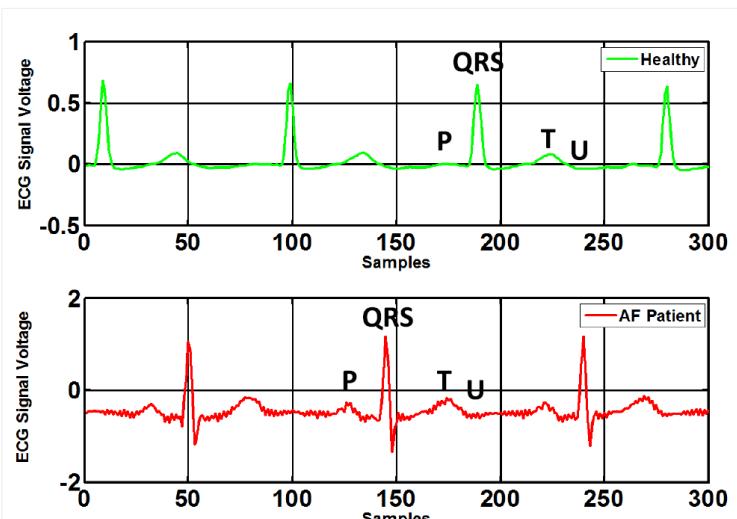


Figure 5: ECG signal of healthy person (top) and AF patient (bottom)

AF occurs in 2% of the population, and increases to 6% by the age of 65. The most serious complication of AF is thromboembolic stroke, which leads to permanent disability or even death. Since in many cases the symptoms are initially imperceptible to patients, diagnosing it as soon as possible becomes difficult, for this reason with the current technological progress, diagnostic tools can be included in wearable devices, for example in smart watches or in affordable medical devices^[d].

2. Notation and relevant definitions

We will now introduce the computational models used.

2.1. Artificial neural network

An artificial neural network (ANN) is an interconnected group of nodes, inspired by a simplification of neurons in a brain. As in Figure 6 each circular node represents an artificial neuron and a line represents a connection from the output of one artificial neuron to the input of another.

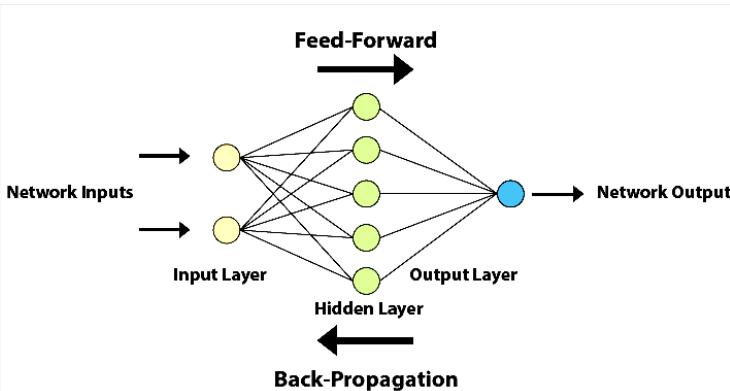


Figure 6: artificial neural network scheme

Typically neural networks are obtained through the combination of simple predictor of the form $g(x) = \sigma(w^T x)$. The function $\sigma: \mathbb{R} \rightarrow \mathbb{R}$ is known as activation function^[12].

To define the neural computation we must specify: the neural model, the model dimensions, the configuration procedure^[11].

a) Neural model

Neural model is composed by activation function and network topology.

Common activation function are: binary step, linear activation, sigmoid, tanH, ReLU, softmax, swish, etc...

The neural network topology represents the way in which neurons are connected to form a network. In other words, the neural network topology can be seen as the relationship between the neurons by means of their connections. The topology of a neural network plays a fundamental role in its functionality and performance. Some famous networks are: feed-forward NN, regulatory feed-

back networks, radial basis function network, recurrent neural network, modular neural network, etc...

b) Configuration procedure

Configuration procedure is composed by: configuration algorithm, training set, validation set.

Configuration algorithm must be chosen based on the learning paradigm: supervised, unsupervised and reinforcement.

In supervised learning the data set contain both the data points \mathcal{X} and the labels \mathcal{Y} . The learning task is to produce the desired output y for each input x . A cost function ℓ is used to estimate the correctness of the predicted label \hat{y} compared to the desired output y .

The simplest division of the data-set is using the Pareto principle, that divide in 80/20 the training and the test set.

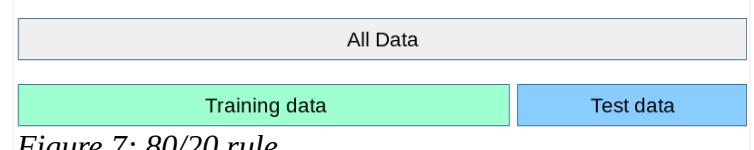


Figure 7: 80/20 rule

When evaluating different settings for estimators, there is still a risk of over-fitting on the test set because the parameters can be tweaked until the estimator performs optimally. This way, knowledge about the test set can “leak” into the model and evaluation metrics no longer report on generalization performance. To solve this problem, yet another part of the data-set can be held out as a so-called “validation set”: training proceeds on the training set, after which evaluation is done on the validation set, and when the experiment seems to be successful, final evaluation can be done on the test set.

However, by partitioning the available data into three sets, we drastically reduce the number of samples which can be used for learning the model, and the results can depend on a particular random choice for the pair of (train, validation) sets.

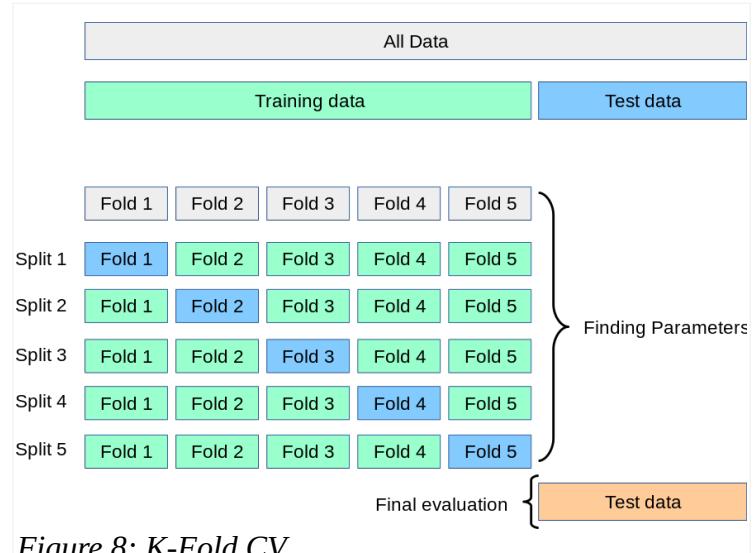


Figure 8: K-Fold CV

A solution to this problem is a procedure called cross-validation (CV). A test set should still be held out for final evaluation, but the validation set is no longer needed when doing CV. In the basic approach, called K-Fold CV (Figure 8), the training set is split into k smaller sets^[h].

Instead unsupervised learning looks for previously undetected patterns in a data set with no pre-existing labels.

Reinforcement learning minimize long-term cost modifying the network's weights. At each point in time an action is performed and an observation is received with a cost. At this point the algorithm/agent decides whether to perform new actions to uncover their cost or to exploit prior learning. In this case NN is used as the learning component.

2.2. Feed-forward neural network

In a feed-forward neural network connections between units do not form loops and information only moves in one direction, forward, with respect to entry nodes, through hidden nodes (if any) to exit nodes. Feed-forward NN computes a function $f: \mathbb{R}^d \rightarrow \mathbb{R}^n$. A parameter $w_{ij} \in \mathbb{R}$ (called weight) is associated with every edge (i, j) . NNs are trained using algorithms that reduce the training error. Fixed a cost function ℓ , an example (x_t, y_t) , defined $\ell_t(W) = \ell(f_{G, W, \sigma}(x_t), y_t)$ and Z_t as the index of a random training example, then the standard training algorithm for NNs is stochastic gradient descent:

$$w_{i,j} \leftarrow w_{i,j} - \eta_t \frac{\partial \ell_z(W)}{\partial w_{i,j}} : (i, j) \in E \quad (1)$$

This procedure is known as error back-propagation algorithm^[12].

2.3. Convolutional neural network

Convolutional neural networks (CNN) function like all feed-forward neural networks: an input layer, one or more hidden layers, which perform calculations using activation functions, and an output layer with the result. The difference is precisely the convolution in place of general matrix multiplication. The typical architecture of a CNN is formed by: convolutional layer, pooling layer, ReLu layer, fully connected layer and loss layer.

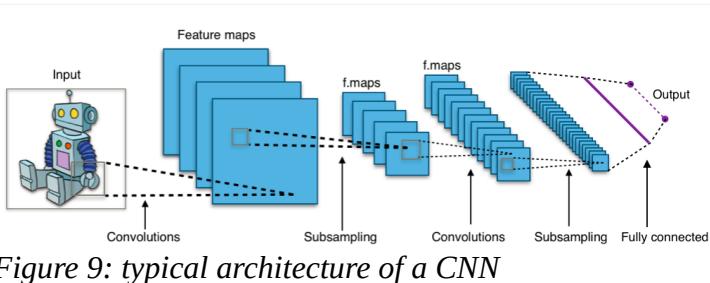


Figure 9: typical architecture of a CNN

a) Convolution

Discrete convolution is an operation between two functions f and h that produce a third function G which consists in integrating the product between the first and the second translated by a certain value. For complex-valued function f and h defined on the set \mathbb{Z} the discrete convolution G of f and h is given by^[g]:

$$G[m, n] = (f * h)[m, n] \quad (2)$$

$$(f * h)[m, n] \stackrel{\text{def}}{=} \sum_j \sum_k h[j, k] \cdot f[m-j, n-k] \quad (3)$$

Input Image						Kernel	Feature Map
10	10	10	10	10	10		0 0 0 0
10	10	10	10	10	10		40 40 40 40
10	10	10	10	10	10		40 40 40 40
0	0	0	0	0	0		
0	0	0	0	0	0		
0	0	0	0	0	0		
0	0	0	0	0	0		

Figure 10: convolution

2.4. QRS recognition algorithms

QRS recognition algorithms are used to facilitate the annotation of the QRS complex in databases.

Various classes of QRS recognition algorithms have been proposed in the literature, which can be classified according to their complexity and performance. The Pan-Tompkins algorithm is one of the most used methods for real-time recognition of the QRS complex from the ECG signal^[13].

The performance of the method was tested on an annotated arrhythmia database and evaluated also in presence of noise. Pan and Tompkins reported that the 99.3% of QRS complexes was correctly detected^[e].

3. Convolutional neural networks and AF detection

We will now introduce ten methodologies for AF detection using convolutional neural network.

3.1. Time-frequency analysis and CNN (detect 12 heart rhythm)

Wu, Lan, Yang, and Nie^[1] proposed a method formed of three steps: preprocessing, time-frequency transform and the convolutional neural network. This method is able to recognize 12 different heart rhythms:

1. normal sinus rhythm (NSR);
2. paced rhythm (P);

3. atrial bigeminy (AB);
4. atrial fibrillation (AF);
5. atrial flutter (AFL);
6. ventricular flutter (VF);
7. first degree heart block (BI);
8. premature ventricular contractions (PVC);
9. sinus bradycardia (SBR);
10. ventricular tachycardia (VT);
11. supraventricular tachy-arrhythmia (SVTA);
12. noise and signal contaminated by noise.

The fact that this method has not specialized only on atrial fibrillation, and that its output consists in listing the percentage of the input belonging to these 12 classes, makes it in addition to having given excellent results (97%) one of the best.

a) Database

The authors used 6 different databases:

1. MIT-BIH arrhythmia;
2. MIT-BIH malignant ventricular arrhythmia;
3. MIT-BIH atrial fibrillation;
4. Long-term AF;
5. MIT-BIH normal sinus rhythm;
6. MIT-BIH noise stress test.

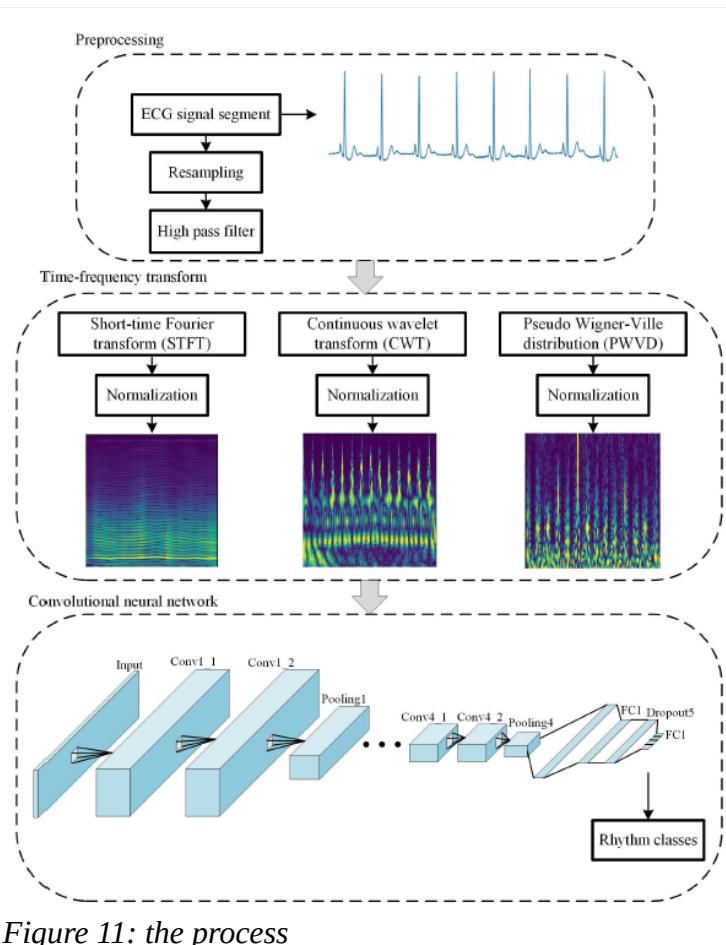


Figure 11: the process

b) Preprocessing

The ECG signal is formed of 12 leads and need to be preprocessed, so the signal was splitted in segments of 10s (using rhythms annotations included in the databases) and resampled to 125Hz. Then a second order high-pass filter with a cutoff frequency of 0.5Hz was used to remove the baseline of each signal.

The “MIT-BIH noise stress test” (it contains noise from baseline wander, muscle artifact and electrode motion artifact) was used to add noise to signals to make the network more reliable to noise. To the signal x was added the noise signal n multiplied by the gain a

$$y = x + a \cdot n \quad (4)$$

The gain a is calculated using the power of the raw signal and the power of the noise signal.

c) Time-frequency transform

Time-frequency analysis is one of the important methods to process non-stationary signals and provides information on time domain and frequency domain.

The authors use three different methods: short-time Fourier transform (STFT), continuous wavelet transformation (CWT) and pseudo Wigner-Ville distribution (PWVD).

The STFT of the sequence $x(t)$ is defined as:

$$STFT(t, w) = \int_{-\infty}^{+\infty} x(\tau) w(\tau - t) e^{-j\omega\tau} d\tau \quad (5)$$

where $w(t)$ is the window function of 2s and the step length is 0.08s.

The CWT is defined as:

$$CWT(a, b) = \int_{-\infty}^{+\infty} x(t) \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) dt \quad (6)$$

where a is the scale factor and b is the time shift factor, $\psi(t)$ is the Morlet wavelet basis:

$$\psi(t) = \exp\left(-\frac{t^2}{2}\right) \cos(5t) \quad (7)$$

At last, the PWVD is defined as:

$$PWVD(t, w) = \int_{-\infty}^{+\infty} w(\tau) x(t + \frac{\tau}{2}) \bar{x}(t - \frac{\tau}{2}) e^{-j\omega\tau} d\tau \quad (8)$$

with \bar{x} the complex conjugate of x .

After the time-frequency transform (one of this) we can calculate the time-frequency distribution matrix as:

$$|Y(a, b)| = \sqrt{Y^2(a, b)} \quad (9)$$

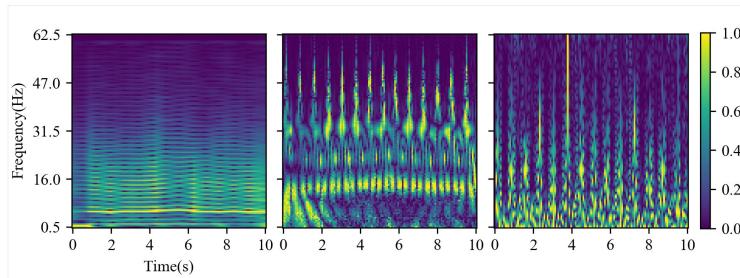


Figure 12: STFT, CWT & PWVD

Above the results of the three methods.

d) CNN

The network is formed by a convolutional block and a fully connected layer.

The convolutional block is formed by the concatenation of a block repeated 4 times. This block is formed by:

1. Convolution layer: 64 kernels (5×5 step 1), padding same, ReLU;
2. Convolution layer: 64 kernels (5×5 step 1), padding same, ReLU;
3. Max pool layer: (2×2);
4. Dropout layer: dropout rate 0.3.

The fully connected layer is formed by:

1. Flatten layer;
2. Fully Connected layer: 128 cells, ReLu;
3. Dropout layer: dropout rate 0.5;
4. Fully Connected layer: 12 outputs, Softmax.

The last layer outputs the probability for each of the 12 different heart rhythms.

e) Training method

The authors used a 5-fold cross validation with the cross-entropy as the loss function:

$$\ell = -\sum_{i=1}^n y_i \log(\hat{y}_i) \quad (10)$$

and the root mean square prop (RMSprop) method was used to update the weights of the network:

$$w_t = w_{t-1} - \alpha \frac{dw}{\sqrt(s_{dw}) + \epsilon} \quad (11)$$

where α is the learning rate, s_{dw} is the accumulation of momentum and $\epsilon > 0$.

f) Results

Four metrics where used to evaluate the three methods, the ranking was: STFT, CWT, PWVD.

Table 1: classification performance

Method	Accuracy	Sensitivity	Specificity	F1
STFT	96.65	96.47	99.68	96.27
CWT	95.26	94.71	99.55	94.80
PWVD	92.07	92.19	99.25	92.26

3.2. Lightweight CNN

Lai, Zhang, Bu, Su and Ma^[2] Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum.

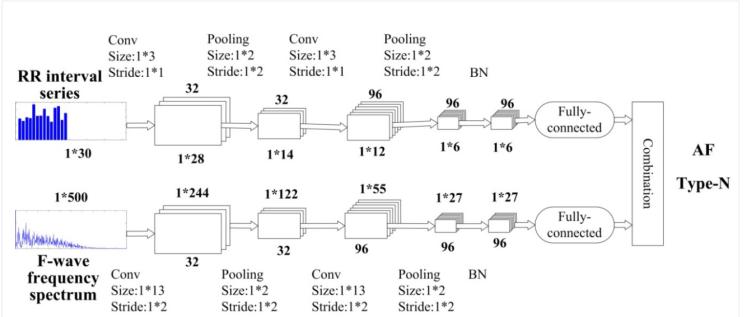
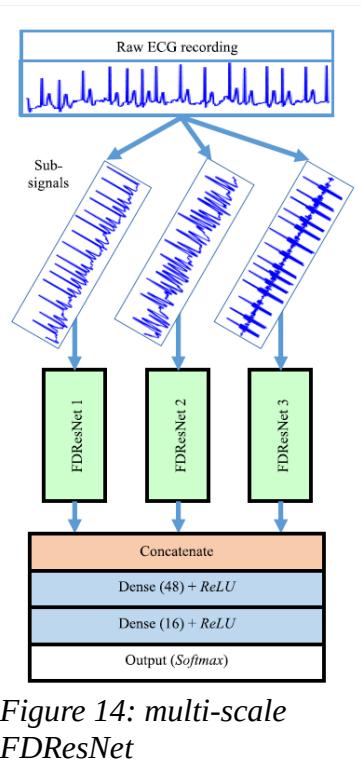


Figure 13: lightweight CNN

3.3. Multi-scale decomposition enhanced residual CNN

Cao, Yao and Chen^[3] Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum. Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum.



3.4. Dual heartbeat coupling based on CNN

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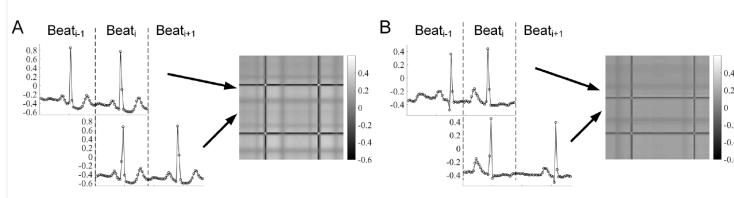
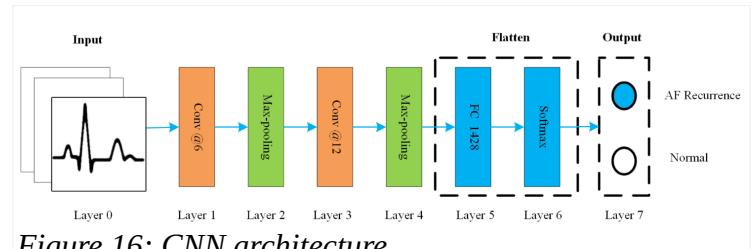


Figure 15: Dual-beat coupling matrix computed from two pairs of adjacent beats. A) Coupling matrix of beats originating from the sinus mode. B) Coupling matrix from a supraventricular ectopic beat.

3.5. CNN with SVM

Li, Feng, Wu, Yang, Bai and Yang^[5] Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum.



3.6. Deep CNN

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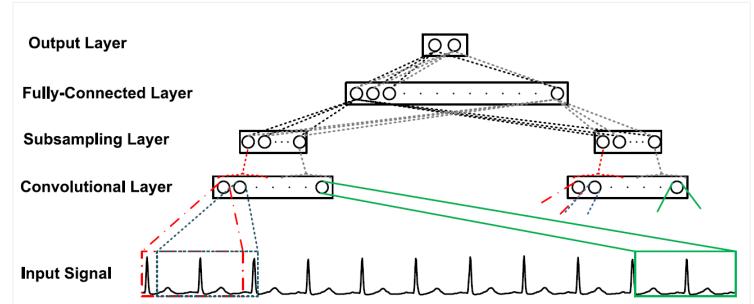
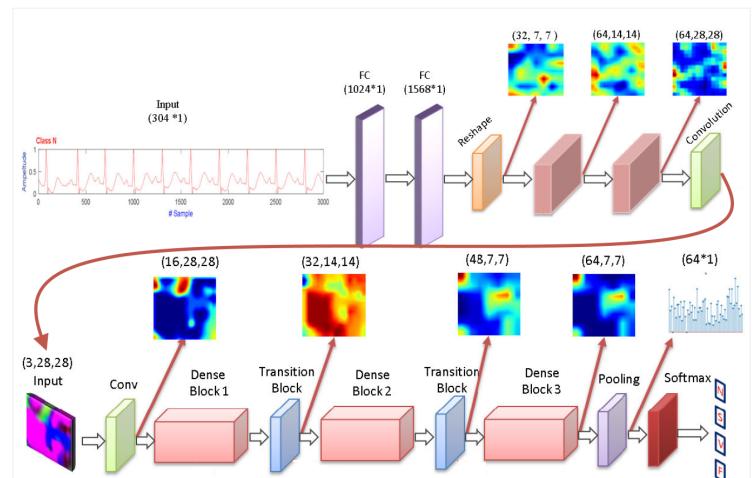


Figure 17: overall structure of the CNN

3.7. Dense CNN with focal loss and image generation

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3.8. STFT-based spectrogram and CNN

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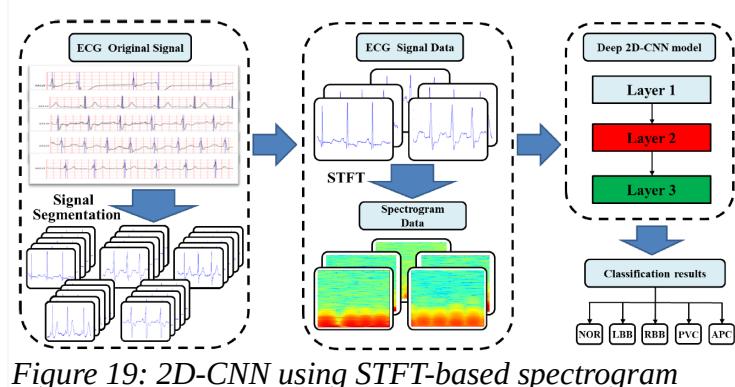


Figure 19: 2D-CNN using STFT-based spectrogram

3.9. Gray-level co-occurrence matrix enhanced CNN

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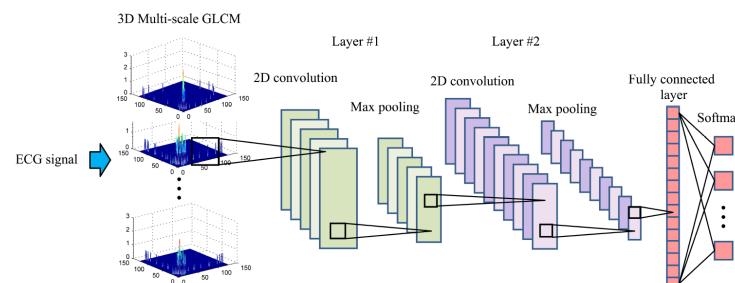


Figure 20: general architecture

3.10. Multiscaled fusion of deep CNN

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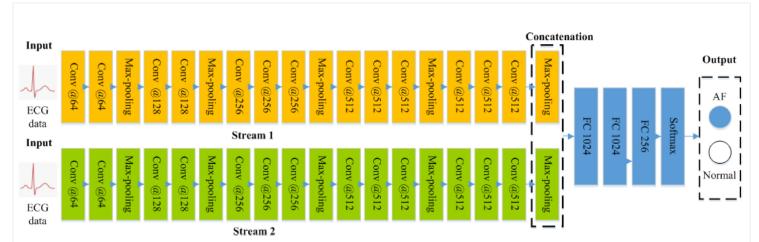


Figure 21: architecture of the MS-CNN

4. Results

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5. Discussion

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6. Conclusion

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