## I. Publications in Indicator B4

**B4.1: Jekova I, Krasteva V, Ménétré S, Stoyanov T, Christov I, Fleischhackl R, Schmid J-J, Didon J-P. (2009) Bench study of the accuracy of a commercial AED arrhythmia analysis algorithm in the presence of electromagnetic interference. *Physiological Measurement*, vol. 30, pp. 695-705, DOI: 10.1088/0967-3334/30/7/012, ISSN: 0967-3334, IOP Publishing, ISI IF: 1.43, Q3 (Web of Science),** https://iopscience.iop.org/article/10.1088/0967-3334/30/7/012

**Abstract**

This paper presents a bench study on a commercial automated external defibrillator (AED). The objective was to evaluate the performance of the defibrillation advisory system and its robustness against electromagnetic interferences (EMI) with central frequencies of 16.7, 50 and 60 Hz. The shock advisory system uses two 50 and 60 Hz band-pass filters, an adaptive filter to identify and suppress 16.7 Hz interference, and a software technique for arrhythmia analysis based on morphology and frequency ECG parameters. The testing process includes noise-free ECG strips from the internationally recognized MIT-VFDB ECG database that were superimposed with simulated EMI artifacts and supplied to the shock advisory system embedded in a real AED. Measurements under special consideration of the allowed variation of EMI frequency (15.7–17.4, 47–52, 58–62 Hz) and amplitude (1 and 8 mV) were performed to optimize external validity. The accuracy was reported using the American Heart Association (AHA) recommendations for arrhythmia analysis performance. In the case of artifact-free signals, the AHA performance goals were exceeded for both sensitivity and specificity: 99% for ventricular fibrillation (VF), 98% for rapid ventricular tachycardia (VT), 90% for slow VT, 100% for normal sinus rhythm, 100% for asystole and 99% for other non-shockable rhythms. In the presence of EMI, the specificity for some non-shockable rhythms (NSR, N) may be affected in some specific cases of a low signal-to-noise ratio and extreme frequencies, leading to a drop in the specificity with no more than 7% point. The specificity for asystole and the sensitivity for VF and rapid VT in the presence of any kind of 16.7, 50 or 60 Hz EMI simulated artifact were shown to reach the equivalence of sensitivity required for non-noisy signals. In conclusion, we proved that the shock advisory system working in a real AED operates accurately according to the AHA recommendations without artifacts and in the presence of EMI. The results may be affected for specificity in the case of a low signal-to-noise ratio or in some extreme frequency setting.

**B4.2: Krasteva V, Jekova I, Ménétré S, Stoyanov T, Didon JP. (2011) Influence of Analysis Duration on the Accuracy of a Shock Advisory System. *Computing in Cardiology*, vol. 38, pp. 537-540, ISSN: 2325-8861, IEEE, SJR: 0.23, Q3 (Scopus),** https://ieeexplore.ieee.org/document/6164621

**Abstract**

This study evaluates the influence of analysis duration on the accuracy of AED shock advisory system (SAS), which is adapted to provide 'Shock'/'No Shock' decision in real time at every second from 2s to 10s. MIT-BIH Malignant Ventricular Arrhythmia database is used for validation of the SAS accuracy on a computer. Four basic ECG criteria used in the presented SAS are evaluated: heart rate, slope uniformity of positive vs. negative peaks, deflections from signal extrema and signal mean in a narrow frequency band for enhancement of the QRS complexes. They show significant differences for shockable and non-shockable rhythms, considering all analysis durations. The presented SAS with analysis duration from 2s to 10s is fully compliant with the AHA performance goal for AEDs. Short ECG episodes, however, require verification for consistency of the rhythm over time.

**B4.3: Didon JP, Krasteva V, Ménétré S, Stoyanov T, Jekova I. (2011) Shock advisory system with minimal delay triggering after end of chest compressions: Accuracy and gained hands-off time. *Resuscitation*, vol. 82 (S2), pp. S8-S15, DOI: 10.1016/S0300-9572(11)70145-9, ISSN: 0300-9572, Elsevier, ISI IF: 3.601, Q1 (Web of Science),** https://www.sciencedirect.com/science/article/pii/S0300957211701459

**Abstract**

*Aims:* Shortening hands-off intervals can improve benefits from defibrillation. This study presents the performance of a shock advisory system (SAS), which aims to decrease the pre-shock pauses by triggering fast rhythm analysis at minimal delay after end of chest compressions (CC).
*Methods:* The SAS is evaluated on a database of 1301 samples from 311 out-of-hospital cardiac arrests (OHCA) from automated external defibrillators (AEDs). The following rhythms are identified: 788 asystoles (ASYS), 20 normal sinus rhythms (NSR), 394 other non-shockable rythms (ONS), 81 ventricular fibrillations (VF), 18 rapid ventricular tachycardias (VThi). SAS is launched in two-stages: first stage for accurate detection of actual end of CC (REoCC); second stage for early “Shock”/“No-Shock” decision by using all available artifact-free ECG signals after REoCC during 3,5,7 s.
*Results:* Performance of the presented SAS versus AEDs is compared. The median hands-off time gained from earlier starting of ECG analysis is 5.8 s and for earlier shock advice is 12.5 s to 8.5 s when SAS rhythm analysis lasts 3 s to 7 s. The SAS accuracy at 3–7 s is: specificity 97.7–98.9% (ASYS), 100–100% (NSR), 98.5–99.2% (ONS); sensitivity 91.4–98.8% (VF), 88.9–96.7% (VThi).
*Conclusion:* This study indicates that shortening the pre-shock hands-off pause by more efficient management of the SAS process in AEDs is possible. For analysis duration of 5 s (7 s), the delay between the end of chest compressions and the shock advice can be reduced by 10.5 s (8.5 s) median, while AHA requirements for rhythm detection accuracy are met. The use of this solution in AEDs could provide more reliable rhythm analysis than methods applying filtering techniques during CC.

**B4.4: *K* Krasteva V, Jekova I, Stoyanov T, Ménétré S, Didon JP. (2013) Performance of Heart Rhythm Analysis during Chest Compressions in Out-of-Hospital Cardiac Arrest. *Computing in Cardiology*, vol. 40, pp. 1091-1094, ISSN: 2325-8861, IEEE, SJR: 0.239, Q3 (Scopus),** https://ieeexplore.ieee.org/document/6713571

**Abstract**

This study aims to validate a shock advisory system in automated external defibrillators (AEDs) dedicated for ECG analysis during chest compressions (CC), guiding the rescuer to stop CC for rhythms which should be terminated by a defibrillation shock and to continue CC for non-shockable rhythms. The test-validation on a large database of out-of-hospital cardiac arrest interventions shows that the performance can be improved by increasing the duration of analysis. The combination of 3 successive analyses (delaying the decision to 14s after start of analysis) achieves sensitivity of 89.4% (135/151) – ventricular fibrillations, specificity of 98.7% (73/74) – normal sinus rhythms, 81.2% (1357/1671) – asystoles, 89.6% (566/632) – other non-shockable rhythms. Several examples are shown to illustrate the reconstructed ECG during CC that can be visually interpreted with certainty. Improving specificity of ECG analysis during CC is of tremendous importance preventing against frequent false positive interrupting the rescuer and the patient CC-treatment.

**B4.5: Jekova I, Stoyanov T, Dotsinsky I. (2017) Arrhythmia Classification via Time and Frequency Domain Analyses of Ventricular and Atrial Contractions. *Computing in Cardiology*, vol. 44, DOI: 10.22489/CinC.2017.345-029, pp. 1-4, ISSN: 2325-8861, IEEE, SJR: 0.191, Q3 (Scopus),** https://ieeexplore.ieee.org/document/8331739

**Abstract**

Atrial fibrillation (AF) is associated with significant risk of heart failure and consequent death. Its episodic appearance, the wide variety of arrhythmias exhibiting irregular AF-like RR intervals and noises accompanying the ECG acquisition, impede the reliable AF detection. Therefore, the Computing in Cardiology Challenge 2017 organizers encourage the development of methods for classification of short, single-lead ECG as AF, normal sinus rhythm (NSR), other rhythm (OR), or noisy signal. The arrhythmia classification module presented in this paper involves procedures for QRS detection and classification, P-waves detection, feature calculation in the time and frequency domains. The applied decision rule is a classification tree. The scores over the training (test subset) [whole test] datasets are: FNSR=0.82(0.81); FAF=0.62(0.61); FOR=0.61(0.53), F1=0.68 (0.65) [0.64].

**B4.6: Krasteva V, Ménétré S, Jekova I, Stoyanov, T, Jost D, Frattini B, Lemoine S, Lemoine F, Thomas V, Didon JP. (2018) Comparison of pediatric and adult ECG rhythm analysis by automated external defibrillators during out-of-hospital cardiac arrest. *Computing in Cardiology*, vol. 45, DOI: 10.22489/CinC.2018.159, pp. 1-4, ISSN:2325-887X, IEEE, SJR: 0.202, Q3 (Scopus),** https://ieeexplore.ieee.org/document/8743731

**Abstract**

This study validates the performance of a commercial automated external defibrillator (AED) on pediatric out-of-hospital cardiac arrest interventions. It shows that the AED with settings validated for adults does not worsen its performance in children, except for rapid non-shockable rhythms (-2%). Further, this study compares 14 behavioral ECG characteristics (6 morphological, 4 band-pass QRS filter, 4 spectral) on adult and pediatric rhythms, highlighting significant rhythm-specific changes. Discriminant models trained on adults and tested on pediatrics highlight 6 features with the most powerful AUC>0.9 and the most robust AUC(Pediatric-Adult)>- 0.025. The design of AED shock advisory algorithm, equally safe for adults and pediatrics is possible if the embedded ECG analysis features fulfil the above criteria.

**B4.7: Krasteva V, Christov I, Naydenov S, Stoyanov T, Jekova I. (2021) Application of Dense Neural Networks for Detection of Atrial Fibrillation and Ranking of Augmented ECG Feature Set. *Sensors*, vol. 21 (20), 6848, pp. 1-35, DOI: 10.3390/s21206848, ISSN: 1424-8220, MDPI, ISI IF: 3.847, Q1 (Web of Science),** https://www.mdpi.com/1424-8220/21/20/6848

**Abstract**

Considering the significant burden to patients and healthcare systems globally related to atrial fibrillation (AF) complications, the early AF diagnosis is of crucial importance. In the view of prominent perspectives for fast and accurate point-of-care arrhythmia detection, our study optimizes an artificial neural network (NN) classifier and ranks the importance of enhanced 137 diagnostic ECG features computed from time and frequency ECG signal representations of short single-lead strips available in 2017 Physionet/CinC Challenge database. Based on hyperparameters' grid search of densely connected NN layers, we derive the optimal topology with three layers and 128, 32, 4 neurons per layer (DenseNet-3@128-32-4), which presents maximal F1-scores for classification of Normal rhythms (0.883, 5076 strips), AF (0.825, 758 strips), Other rhythms (0.705, 2415 strips), Noise (0.618, 279 strips) and total F1 relevant to the CinC Challenge of 0.804, derived by five-fold cross-validation. DenseNet-3@128-32-4 performs equally well with 137 to 32 features and presents tolerable reduction by about 0.03 to 0.06 points for limited input sets, including 8 and 16 features, respectively. The feature reduction is linked to effective application of a comprehensive method for computation of the feature map importance based on the weights of the activated neurons through the total path from input to specific output in DenseNet. The detailed analysis of 20 top-ranked ECG features with greatest importance to the detection of each rhythm and overall of all rhythms reveals DenseNet decision-making process, noticeably corresponding to the cardiologists' diagnostic point of view.

**B4.8: Didon JP, Ménétré S, Jekova I, Stoyanov T, Krasteva V. (2021) Analyze Whilst Compressing algorithm for detection of ventricular fibrillation during CPR: A comparative performance evaluation for automated external defibrillators. *Resuscitation*, vol. 160, pp. 94-102, DOI: 10.1016/j.resuscitation.2021.01.018, ISSN: 0300-9572, Elsevier, ISI IF: 6.251**, https://www.sciencedirect.com/science/article/pii/S0300957221000265

**Abstract**

*Objective:* The aim of this study was to present new combination of algorithms for rhythm analysis during cardiopulmonary resuscitation (CPR) in automated external defibrillators (AED), called Analyze Whilst Compressing (AWC), designed for decreasing pre-shock pause and early stopping of chest compressions (CC) for treating refibrillation.

*Methods:* Two stages for AED rhythm analysis were presented, namely, “Standard Analysis Stage” (conventional shock-advisory analysis run over 5 s after CC interruption every two minutes) and “AWC Stage” (two-step sequential analysis process during CPR). AWC steps were run in presence of CC (Step1), and if shockable rhythm was detected then a reconfirmation step was run in absence of CC (Step2, analysis duration 5 s).

*Results:* In total 16,057 ECG strips from 2916 out-of-hospital cardiac arrest (OHCA) patients treated with AEDs (DEFIGARD TOUCH7, Schiller Médical, France) were subjected patient-wise to AWC training (8559 strips, 1604 patients) and validation (7498 strips, 1312 patients). Considering validation results, “Standard Analysis Stage” presented ventricular fibrillation (VF) sensitivity Se = 98.3% and non-shockable rhythm specificity Sp>99%; “AWC Stage” decision after Step2 reconfirmation achieved Se = 92.1%, Sp>99%.

*Conclusion:* AWC presented similar performances to other AED algorithms during CPR, fulfilling performance goals recommended by standards. AWC provided advances in the challenge for improving CPR quality by: (i) not interrupting chest compressions for prevalent part of non-shockable rhythms (66-83%); (ii) minimizing pre-shock pause for 92.1% of VF patients. AWC required hands-off reconfirmation in 34.4% of cases. Reconfirmation was also common limitation of other reported algorithms (25.7-100%) although following different protocols for triggering chest compression resumption and shock delivery.

**B4.9: Garvanski I, Matveev M, Krasteva V, Stoyanov T, Simova Y. (2022) On a Possible Approach to Risk Prediction of Recurrence of Atrial Fibrillation after Catheter Ablation According to Data from the Pre-procedure Period. *International Journal Bioautomation*, vol. 26 (1), pp. 37-66, DOI: 10.7546/ijba.2022.26.1.000869, ISSN: 1314-1902, SJR: 0.159, Q4 (Scopus),** https://www.biomed.bas.bg/bioautomation/2022/vol_26.1/files/26.1_03.pdf

**Abstract**

The aim of the study is to identify and evaluate predictors of recurrent paroxysms of atrial fibrillation (AF) paroxysms based on data from the preprocedural period among personal indices, history, comorbidities, ultrasound examination, and morphological components of f-waves, such as spectral amplitude and frequency. 39 patients with antral pulmonary vein isolation using radiofrequency or cryoenergy were included. Spectral analysis of f-waves was performed by fast Fourier transform of the ECG signal after suppression of the T-wave and QRS-complex. The performed U-test for the difference between the amplitude and frequency indicators in the groups without and with recurrence of AF shows a significant difference between the amplitude values in the two studied groups of patients. Through a stepwise discriminant analysis of a total of 14 indicators, 5 reliably separated groups without and with recurrence were determined: Echo LV-EF, spectral amplitude of f-waves, heart failure, Stroke/TIA, diabetes. The discriminator synthesized on these indices classified among the 39 patient – 25 without relapse (group 1) and 14 with relapse (group 2), 3 patients wrong from group 1 to group 2 (false positive), or 12%, and 1 patient was wrong from group 2 to group 1 (false negative), or 7.1%. These results give grounds to accept the hypothesis that it is possible to develop a decision rule for determining the degree of risk of post-

procedural recurrence of AF from pre-procedural period data.

**B4.10: Vassilev PM, Stoyanov T, Todorova LP, Marazov A, Andonov V, Ikonomov I. (2023) Orderings over Intuitionistic Fuzzy Pairs Generated by the Power Mean and the Weighted Power Mean. *Mathematics*, vol. 11 (13), 2893, pp. 1-15, DOI: 10.3390/math11132893, ISSN: 2227-7390, MDPI, ISI IF: 2.4, Q1 (Web of Science),** https://www.mdpi.com/2227-7390/11/13/2893

**Abstract**

In the present work, we prove a result concerning an ordering over intuitionistic fuzzy pairs generated by the power mean (Mp) for p > 0. We also introduce a family of orderings over intuitionistic fuzzy pairs generated by the weighted power mean (Map) and prove that a similar result holds for them. The considered orderings in a natural way extend the classical partial ordering and allow the comparison of previously incomparable alternatives. In the process of proving these properties, we establish some inequalities involving logarithms which may be of interest by themselves. We also show that there exists p > 0 for which a finite set of alternatives, satisfying some reasonable requirements, some of which were not comparable under the classical ordering, has all its elements comparable under the new ordering. Finally, we provide some examples for the possible use of these orderings to a set of alternatives, which are in the form of intuitionistic fuzzy pairs as well as to results from InterCriteria Analysis.

**B4.11: Krasteva V, Stoyanov T, Schmid R, Jekova I. (2024) Delineation of 12-Lead ECG Representative Beats Using Convolutional Encoder–Decoders with Residual and Recurrent Connections. *Sensors*, vol. 24 (14), 4645, pp. 1-31, DOI: 10.3390/s24144645, ISSN: 1424-8220, MDPI, ISI IF: 3.4,** https://www.mdpi.com/1424-8220/24/14/4645

**Abstract**

The aim of this study is to address the challenge of 12-lead ECG delineation by different encoder–decoder architectures of deep neural networks (DNNs). This study compares four concepts for encoder–decoders based on a fully convolutional architecture (CED-Net) and its modifications with a recurrent layer (CED-LSTM-Net), residual connections between symmetrical encoder and decoder feature maps (CED-U-Net), and sequential residual blocks (CED-Res-Net). All DNNs transform 12-lead representative beats to three diagnostic ECG intervals (P-wave, QRS-complex, QT-interval) used for the global delineation of the representative beat (P-onset, P-offset, QRS-onset, QRS-offset, T-offset). All DNNs were trained and optimized using the large PhysioNet ECG database (PTB-XL) under identical conditions, applying an advanced approach for machine-based supervised learning with a reference algorithm for ECG delineation (ETM, Schiller AG, Baar, Switzerland). The test results indicate that all DNN architectures are equally capable of reproducing the reference delineation algorithm’s measurements in the diagnostic PTB database with an average P-wave detection accuracy (96.6%) and time and duration errors: mean values (−2.6 to 2.4 ms) and standard deviations (2.9 to 11.4 ms). The validation according to the standard-based evaluation practices of diagnostic electrocardiographs with the CSE database outlines a CED-Net model, which measures P-duration (2.6 ± 11.0 ms), PQ-interval (0.9 ± 5.8 ms), QRS-duration (−2.4 ± 5.4 ms), and QT-interval (−0.7 ± 10.3 ms), which meet all standard tolerances. Noise tests with high-frequency, low-frequency, and power-line frequency noise (50/60 Hz) confirm that CED-Net, CED-Res-Net, and CED-LSTM-Net are robust to all types of noise, mostly presenting a mean duration error < 2.5 ms when compared to measurements without noise. Reduced noise immunity is observed for the U-net architecture. Comparative analysis with other published studies scores this research within the lower range of time errors, highlighting its competitive performance.

## II. Publications in Indicator G7

**G7.1: Andonov V, Stefanova-Pavlova M, Stoyanov T, Angelova M, Cook G, Klein B, Atanassov K, Vassilev P. (2012) Generalized net model for telehealth services. *Proc. of the 6th IEEE Int. Conf. "Intelligent Systems"*, pp. 221-224, DOI: 10.1109/IS.2012.6335220, ISSN: 1541-1672, IEEE,** https://ieeexplore.ieee.org/document/6335220

**Abstract**

During last 30 years, the generalized nets are used as a tool for modelling of different processes in medicine. In the present paper, an application of the apparatus of generalized nets to assistive technology, namely to telehealth services and the advantages of using such model, is discussed.

**G7.2: Neycheva T, Stoyanov T, Abacherli R, Christov I. (2013) High resolution 16-channel ECG tester simulator for online digital-to-analogue conversion of data from PC. *Computing in Cardiology*, vol. 40, pp. 457-460, ISSN: 2325-8853, IEEE, SJR:0.234, Q3 (Scopus),** https://ieeexplore.ieee.org/document/6713412

**Abstract**

Recent design of electrocardiographic simulators should be consistent with the international standard IEC 60601-2-47 issued 2012, which recommends the measurements, detections and interpretative statements of the ECG to be tested by digitized ECGs signals taken from five standard databases. In accordance to this recommendation we designed a high-resolution ECG tester simulator for direct digital- to - analogue conversion of data from PC. The signals selected from a database are sent from the PC to the Simulator via USB. The prototype has 16 independent channels, high sampling frequency of 2 KHz, and 286 nV/bit amplitude respond of the analogue output. The power-line interference is minimized by a galvanic isolation of the communication between the PC and the simulator. The need of build-in circuit for a Wilson Central Terminal is avoided by the use of 12-Standardleads to 8-primary-leads transfer formulas. In-house PC software in Visual C is developed to select and control the operation mode of the simulator. The transmitted signals are real-time visualized on the PC monitor.

**G7.3: Christov I, Neycheva T, Schmid R, Stoyanov T, Abächerli R. (2017) Pseudo real-time low-pass filter in ECG, self-adjustable to the frequency spectra of the waves. *Medical & Biological Engineering & Computing*, vol. 55 (9), pp. 1579-1588, DOI: 10.1007/s11517-017-1625-y, ISSN: 1741-0444, Springer, ISI IF: 1.971, Q2 (Web of Science),** https://link.springer.com/article/10.1007/s11517-017-1625-y

**Abstract**

The electrocardiogram (ECG) acquisition is often accompanied by high-frequency electromyographic (EMG) noise. The noise is difficult to be filtered, due to considerable overlapping of its frequency spectrum to the frequency spectrum of the ECG. Today, filters must conform to the new guidelines (2007) for low-pass filtering in ECG with cutoffs of 150 Hz for adolescents and adults, and to 250 Hz for children. We are suggesting a pseudo-realtime low-pass filter, self-adjustable to the frequency spectra of the ECG waves. The filter is based on the approximation procedure of Savitzky–Golay with dynamic change in the cutoff frequency. The filter is implemented pseudo-realtime (real-time with a certain delay). An additional option is the automatic on/off triggering, depending on the presence/absence of EMG noise. The analysis of the proposed filter shows that the low-frequency components of the ECG (low-power P- and T-waves, PQ-, ST- and TP-segments) are filtered with a cutoff of 14 Hz, the high-power P- and T-waves are filtered with a cutoff frequency in the range of time a maximal preservation of the ECG high-frequency components 20–30 Hz, and the high-frequency QRS complexes are filtered with cutoff frequency of higher than 100 Hz. The suggested dynamic filter satisfies the conflicting requirements for a strong suppression of EMG noise and at the same time a maximal preservation of the ECG high-frequency components.

**G7.4: Stefanova-Pavlova M, Andonov V, Stoyanov T, Angelova M, Cook G, Klein B, Vassilev P, Stefanova E. (2017) Modeling Telehealth Services with Generalized Nets. *Studies in Computational Intelligence*, vol. 657, pp. 279-290, DOI: 10.1007/978-3-319-41438-6_16, ISSN: 1860-949X, Springer International Publishing Switzerland AG, SJR: 0.187, Q4 (Scopus),** https://link.springer.com/chapter/10.1007/978-3-319-41438-6_16

**Abstract**

Generalized Net model of processes, related to tracking the changes in health status (diabetes) of adult patients has been presented. The contemporary state of the art of the telecommunications and navigation technologies allows this model to be extended to the case of active and mobile patient. This requires the inclusion of patient's current location as a new and significant variable of the model. Various opportunities are considered for the retrieval of this information, with a focus on the optimal ones, and a refined Generalized Net model is proposed.

**G7.5: Vassilev P, Stoyanov T. (2018) On Power Mean Generated Orderings Between Intuitionistic Fuzzy Pairs. *Advances in Intelligent Systems and Computing*, vol. 643, pp. 476-481, DOI:10.1007/978-3-319-66827-7_44, ISSN: 2194-5357, Springer International Publishing AG, SJR: 0.174, Q3 (Scopus),** https://link.springer.com/chapter/10.1007/978-3-319-66827-7_44

**Abstract**

In this paper we revisit the topic of orderings between intuitionistic fuzzy pairs and then provide a more general point of view in their introduction. This would allows us to use less strict orderings in producing similarity scores for objects whose evaluations are in the form of intuitionistic fuzzy pair.

**G7.6: Dotsinsky I, Stoyanov T. (2019) Continuously Tested and Used QRS Detection Algorithm: Free Access to the MATLAB Code. *International Journal Bioautomation*, 23 (1), pp. 61-70, DOI: 10.7546/ijba.2019.23.1.61-70, ISSN: 1314-1902, SJR: 0.242, Q3 (Scopus),**
https://biomed.bas.bg/bioautomation/2019/vol_23.1/files/23.1_06.pdf

**Abstract**

Each ECG analysis begins with the detection of the QRS complex, which is the most distinguishable wave for initial investigation. Long ago we published an algorithm for ventricular beats (VB) detection in single ECG lead. The classification of normal QRS complexes are based on the slope, the amplitude and the width of the ECG waves. Other criteria recognize ventricular ectopic beats (EB) by presence of biphasic beats and separate premature EB from the already detected QRS complexes. The aim of this paper is to place the MATLAB program of our algorithm at disposal to the readers (supplementary MATLAB codes) looking forward to more successful ECG investigations.

**G7.7: Dotsinsky I, Stoyanov T, Mihov G. (2020) Power-line Interference Removal from High Sampled ECG Signals Using Modified Version of the Subtraction Procedure. *International Journal Bioautomation*, vol. 24 (4), pp. 381-392, DOI: 10.7546/ijba.2020.24.4.000802, ISSN: 1314-2321, SJR: 0.178, Q4 (Scopus),** https://biomed.bas.bg/bioautomation/2019/vol_23.1/files/23.1_06.pdf

**Abstract**

The acquired ECG signals are often contaminated by residual Power-line Interference (PLI). A lot of methods, algorithms and techniques for PLI reduction have been published over the last few decades. The so called subtraction procedure is known to eliminate almost totally the interference without affecting the signal spectrum. The goal of our research was to develop a heuristic version of the procedure intended for ECG signals with high Sampling Rate (SR) up to 128 kHz. The PLI is extracted from the corrupted signal by technique similar to second order band-pass filter but with practically zero phase error. The sample number as well as the left and right parts outside the

samples belonging to a current sine wave, which is extracted from the contaminated signal, are counted and measured. They are used to compensate the error arising with the shift between the moving averaged free of PLI signal samples and their real position along the linear segments (usually PQ and TP intervals having frequency band near to zero). The here calculated PLI components are appropriately interpolated to 'clean' the dynamically changed in amplitude and position contaminated samples within the non-linear segments (QRS complexes and high T waves). The reported version of the subtraction procedure is tested with 5 and 128 kHz sampled ECG signals. The maximum absolute error is about 20 μV except for the ends of the recordings. Finally, an approach to PLI elimination from paced ECG signals is proposed. It includes pace pulse extraction, signal re-sampling down to 4 kHz and subtraction rocedure implementation followed by adding back the removed pace pulses.

**G7.8: Jekova I, Bortolan G, Stoyanov T, Dotsinsky I. (2020) Multi-type Arrhythmia Classification: Assessment of the Potential of Time and Frequency Domain Features and Different Classifiers. *International Journal Bioautomation*, vol. 24 (2), pp. 153-172, DOI: 10.7546/ijba.2020.24.2.000743, ISSN: 1314-2321, SJR: 0.178, Q4 (Scopus),** https://www.biomed.bas.bg/bioautomation/2020/vol_24.2/files/24.2_05.pdf

**Abstract**

Atrial fibrillation (AF) is associated with significant risk of heart failure and consequent death. Its episodic appearance, the wide variety of arrhythmias exhibiting irregular AF-like RR intervals and noises accompanying the ECG acquisition, impede the reliable AF detection. Therefore, the Computing in Cardiology Challenge 2017 organizers encourage the development of methods for classification of short, single-lead ECG as AF, normal sinus rhythm (NSR), other rhythm (OR), or noisy signal (NOISE). This study presents a set of 118 time and frequency domain feature including descriptors of the RR and PP intervals; QRS and P-wave amplitudes; ECG behavior within the TQ intervals, deviation of the TQ and PQRST segments from their first principle component analysis vector; dominant frequency; regularity index, width and area of the power spectrum estimated for the ECG signal with eliminated QRS complexes. Three classification techniques have been applied over the 118 ECG features – linear discriminant analysis (LDA), classification tree (CT) and neural network (NN) approach. The scores over a test subset are: (i) FNSR = 0.81; FAF = 0.61; FOR = 0.53, F1 = 0.65 for CT, which is the most simple model; (ii) FNSR = 0.82; FAF = 0.62; FOR = 0.53, F1 = 0.66 for LDA, which is the model with the most reproducible accuracy results; (iii) FNSR = 0.86; FAF = 0.74; FOR = 0.57, F1 = 0.72 for NN, which is the most accurate model.

**G7.9: Jekova I, Vassilev P, Stoyanov T, Pencheva T. (2021) InterCriteria Analysis: Application for ECG Data Analysis. *Mathematics*, vol. 9 (8), 854, pp. 1-16, DOI: 10.3390/math9080854, ISSN: 2227-7390, MDPI, ISI-IF: 2.592, Q1 (Web of Science),** https://www.mdpi.com/2227-7390/9/8/854

**Abstract**

The InterCriteria Analysis (ICrA) is based on the mathematical formalisms of index matrices and intuitionistic fuzzy sets. It has been elaborated to discern possible similarities in the behavior of criteria pairs when multiple objects are considered, allowing also the accounting of information uncertainty. The focus of this study is to validate the applicability of ICrA over a large set of ECG criteria extracted for arrhythmia analysis and to evaluate its ability to support the pre-selection of criteria that could be further involved in decision making procedures. ICrA is applied over 88 ECG criteria (resulting in 3828 criteria pairs) calculated for 8528 ECGs from PhysioNet/CinC Challenge 2017 database. Three criteria pairs show strong positive consonance, another 26—positive consonance, while another 15 are in negative consonance. ICrA also reveals lack of dependencies in 98 criteria pairs. The correspondence between our observations (high degrees of agreement/disagreement and lack of dependencies) and our expectations based on knowledge of

the principles involved in the computation of the ECG criteria validates the application of ICrA for reliable evaluation of the relation between different criteria. This potential of ICrA to highlight useful relations between ECG criteria makes it suitable in the ECG pre-processing stage for criteria pre-selection. Thus, optimization of the feature space could be achieved together with minimization of the computations' complexity.

**G7.10: Stoyanov T. (2022) Web-Based Software Tool for Electrocardiogram Annotation. *Lecture Notes in Networks and Systems*, vol. 374, pp. 322-331, DOI: 10.1007/978-3-030-96638-6_34, ISSN:2367-3370, Springer, Cham, SJR: 0.151, Q4 (Scopus),** https://link.springer.com/chapter/10.1007/978-3-030-96638-6_34

**Abstract**

The manual annotation of large multilead ECG databases is a challenge, especially in the context for providing meaningful visualization, easy tools for annotation and simultaneous access from multiple experts via extended Internet connectivity. The aim of this work is to present the development platform and capabilities of internet-based software tool for the purpose of user-friendly manual annotation and delineation of heartbeats in 12-lead ECG databases. The annotation software consists of: (i) server-based application, written in Python under DJango framework with SQLite database manager; and (ii) web-based front-end application, created in Node Package Manager environment under React JavaScript framework. The server-based part contains procedures for managing the ECG records (i.e. receiving and saving ECG signals), saving manually annotated data, and generation of average beats. The front-end application contains: (i) graphical user interface for visualization of 12-lead ECG signals and management of the user input/output commands; (ii) annotation module, which provides tools to mark and correct the positions and type of QRS complexes; (iii) average beat module, which provides an option to switch between leads, provides graphical markers for annotation of fiducial points and time-intervals in the averaged heartbeat waveform and sets the average beat type; and (iv) rhythm type module, which shows the rhythm type and provides a possibility to change it. The software is opened for further developments. The presented annotation tool could be potentially used for annotation of large ECG databases without limitations on the number of ECG leads and number of annotations per ECG recording. This is in line with the new trends for accumulation of large ECG databases from multiple sources, which are the thoughtful platform for development of machine learning and especially deep learning algorithms for ECG signal processing and arrhythmia classification.

## III. Publications in Indicator G8

**G8.1: Matveev M, Naydenov S, Krasteva V, Mudrov N, Stoyanov T. (2005) Assessment of the infarct size from high-resolution ECG computer-based system. *Proc. 14-th Internat. Sci. Conf. "Electronics'2005"*, Sozopol, Sept.21-23, 2005, book 4, pp. 55-60, ISBN 954-438-520-7, Technical University – Sofia,**
https://ecad.tu-sofia.bg/et/2005/pdf/Paper047-M_Matveev.pdf

**Abstract**

The present study describes the implementation of computer-based multichannel ECG system in intensive coronary care unit for monitoring of patients with acute myocardial infarction (AMI), thus providing a convenient method for precise assessment of the infarct size. The ECG PC-based system was designed to acquire, process, analyze, visualize the standard leads, as well as to allow the application of advanced examinations and tests on the acquired high-resolution ECG signals. Fifteen patients with clinical symptoms, ECG and laboratory signs for AMI with ST-elevation from the Department of Internal Medicine "Prof. St. Kirkovic", Medical University - Sofia were examined with the developed ECG system. We studied the approach for analysis of the high-resolution ECG recordings, especially the synthesized VCG leads with some additional transforms, aiming to provide adequate information about the infarct size and localization.

**G8.2: Neycheva T, Stoyanov T. (2007) High-resolution front-end for ECG signal processing. *Proc. 16-th Internat. Sci. Conf. "Electronics'2007"*, Sozopol, Sept.19-21, 2007, book 2, pp. 61-66, ISSN:1313-1842, Technical University – Sofia,**
https://ecad.tu-sofia.bg/et/2007/ET2007%20Book2/Electronic%20Medical%20Equipment/61-Paper-T_Neycheva.pdf

**Abstract**

This paper presents research system with 12 channel high-resolution (24 bits) front-end for ECG signal processing. The implemented high-resolution data conversion makes the system suitable for recording of late potentials which are microvolt-level high-frequency waveforms in the terminal portion of the QRS complex in patients prone to sustained ventricular tachycardia. The front-end consists of 12 channel ECG amplifier built on body potential driving concept. The amplifier outputs are connected to 12 delta-sigma ADCs. The whole ADCs work synchronously at 8 kHz sampling frequency and their output data are transferred to PC via USB. The presented system could be useful in other signal processing applications where multi-channel, high-resolution, data conversion is needed.

**G8.3: Dotsinsky I, Stoyanov T. (2008) Power-line Interference Removal from ECG in Case of Power-line Frequency Variations. *International Journal Bioautomation*, vol. 10, pp. 88-96, ISSN:1312–451X,**
https://www.biomed.bas.bg/bioautomation/2008/vol_10.1/files/10_3.4.pdf

**Abstract**

The original version of the most successful approach for power-line (PL) interference removal from ECG, called subtraction procedure, is based on linear segment detection in the signal and hardware synchronized analogue-to-digital conversion to cope with the PL frequency variations. However, this is not feasible for battery supplied devices and some computer-aided ECG systems. Recent improvements of the procedure apply software measurement of the frequency variations that allow a re-sampling of the contaminated signal with the rated PL frequency followed by interference removal and back re-sampling for restoration of the original time intervals. This study deals with a more accurate software frequency measurement and introduces a notch filtration as alternative to the procedure when no linear segments are encountered for longtime, e.g. in cases of ventricular fibrillation or tachycardia. The result obtained with large PL frequency variations demonstrate very small errors, usually in the range of ±20μV for the subtraction procedure and ±60μV for the notch filtration, the last values strongly depending on the frequency contents of the QRS complexes.

**G8.4: Dotsinsky I, Krasteva V, Jekova I, Christov I, Stoyanov T. (2008) Detection of extrasystoles in the electrocardiogram: a review of methods and algorithms applicable in quasi-real time. *Automation and Informatics*, vol. 4/2008, pp. 25-30, ISSN: 0861-7562, Union of Automation and Informatics "John Atanasov", (in Bulgarian).**

**Abstract**

The rhythmic activity of the heart is regulated by a specialized conduction system that initiates electrical impulses, triggering the atria and ventricles to contract in a precise sequence. In an electrocardiogram (ECG), normal ventricular contractions are represented by relatively uniform QRS complexes, while the intervals between them (RR intervals) reflect the heart rhythm, which typically fluctuates slightly in sync with breathing. However, disruptions in the heart's conduction system can cause abnormal contractions—known as extrasystoles—where the RR intervals and/or QRS complex shape deviate significantly. Atrial (supraventricular) extrasystoles affect only the RR intervals, as the electrical impulse still follows the normal conduction pathway to the ventricles. In contrast, ventricular extrasystoles result in altered QRS complex morphology. While isolated extrasystoles usually do not cause symptoms, frequent occurrences may indicate abnormalities in the heart's depolarization processes, potentially signaling the onset of serious, life-threatening arrhythmias. Automatic detection and classification of ventricular contractions into normal QRS complexes and extrasystoles have been extensively researched for years. This process forms the basis of rhythm analysis used in continuous 24-hour ECG monitoring (via Holter systems) and in patient monitoring systems in intensive care and surgical units to detect and manage cardiac dysfunctions.

**G8.5: Christov I, Jekova I, Krasteva V, Dotsinsky I, Stoyanov T. (2009) Rhythm analysis by heartbeat classification in the electrocardiogram. *International Journal Bioautomation*, vol. 13 (2), pp. 84-96, ISSN: 1312–451X,** https://biomed.bas.bg/bioautomation/2009/vol_13.2/files/13.2_4.2.pdf

**Abstract**

The morphological and rhythm analysis of the electrocardiogram (ECG) is based on ventricular beats detection, wave parameters measurement, as amplitudes, widths, polarities, intervals and relations between them, and a subsequent classification supporting the diagnostic process. Number of algorithms for detection and classification of the QRS complexes have been developed by researchers in the Centre of Biomedical Engineering – Bulgarian Academy of Sciences, and are reviewed in this material. Combined criteria have been introduced dealing with the QRS areas and amplitudes, the wave shapes evaluated by steep slopes and sharp peaks, vector cardiographic (VCG) loop descriptors, RR intervals irregularities. Algorithms have been designed for application on a single ECG lead, a synthesized lead derived by multichannel synchronous recordings, or simultaneous multilead analysis. Some approaches are based on templates matching, cross-correlation or rely on a continuous updating of adaptive thresholds. Various beat classification methods have been designed involving discriminant analysis, the K-th nearest neighbors, fuzzy sets, genetic algorithms, neural networks, etc. The efficiency of the developed methods has been assessed using internationally recognized arrhythmia ECG databases with annotated beats and rhythm disturbances. In general, high values for specificity and sensitivity competitive to those reported in the literature have been achieved.

**G8.6: Krasteva V, Jekova I, Stoyanov T, Didon JP. (2009) Hands-off intervals during cardiopulmonary resuscitation: duration and effect on the ECG analysis. *International Journal Bioautomation*, vol. 13 (4), pp. 29-38, ISSN: 1312–451X,** https://www.biomed.bas.bg/bioautomation/2009/vol_13.4/files/13.4_1.05.pdf

**Abstract**

Recent works are aimed at development of shock advisory systems (SAS) for automated external defibrillators (AEDs), which continuously analyze the electrocardiogram (ECG) during non-

interrupted chest compressions (CC). Being also part of the cardiopulmonary resuscitation (CPR), small ‘hands-off’ intervals (CC pauses) for insufflations are interrupting the CC, and thus the SAS analysis process. This study is applied on 530 CC-contaminated ECG strips taken from168 patients who undergo out-of-hospital resuscitation interventions with AEDs. A statistical study of the short duration CC pauses is performed, showing non-normal distribution with median value of 4seconds, quartile range between 3 and 5 seconds, min-max range between 1 and 10 seconds. Another focus is the effect of skipping the CC pauses on the SAS accuracy by supplying continuous non-linear CC-corrupted ECG signal for analysis. The SAS is tested with different coupling intervals [t1, t2], where t1 is the time before the CC pause, t2 is the time after the CC pause, t1+t2=10 seconds. The SAS accuracy on CC-corrupted linear signals [10s+0s] compared to non-linear signals [9s+1s], [8s+2s], [7s+3s], [6s+4s], [5s+5s] shows insignificant difference ($p>0.05$) for the different arrhythmia: ventricular fibrillation between 86% and 90.3%, normal rhythms between 88.4% and 93.5%, asystole between 80.4% and 87.3%. Several examples illustrate the performance of the SAS analysis process on various CC artefacts and ECG arrhythmias.

**G8.7: Krasteva V, Jekova I, Mudrov N, Stoyanov T. (2009) Automated external defibrillators. Journal of the Bulgarian Academy of Sciences, vol. 4, pp. 13-17, ISSN: 0007-3989, (in Bulgarian).**

**Abstract**

Developments on automatic external defibrillators (AEDs) supporting their specific public access application are presented as follows:

- Defibrillation pulses: waveform optimization and design of Pulsed Biphasic Technology with controlled duty cycle of high-frequency chopped pulses, that has been implemented in commercial AEDs. The advantage is small devices supporting low-energy defibrillation with improved efficacy and less risk for miocardial damage.
- Shock advisory system: development of very accurate and fast algorithm for automatic analysis of the electrocardiogram (ECG) for detection of shockable and non-shockable rhythms. The system has been implemented in commercial AEDs and takes autonomus decision for shock delivery, without interpretation of the rhythm by expert.
- System working during Cardio Pulmonary Resuscitation (CPR). Two modules have been designed: (1) Analysis of ECG corrupted by chest compression artefacts to recommend stopping or continuation of CPR. Adequate accuracy is achieved to provide minimal 'hands-off' intervals and improve the efficacy of resusciatation; (2) feedback to control the CPR quality by measuring the depth and rate of chest compressions. The system is for training or leading the rescuers during CPR.

**G8.8: Stoyanov T, Christov I, Jekova I, Krasteva V. (2010) Online adaptive filter for mains interference suppression in diagnostic electrocardiographs: Cases of amplitude and frequency deviation. *Annual Journal of Electronics*, vol. 4 (2), pp. 150-153, ISSN:1314-0078, Technical University – Sofia.**

**Abstract**

In this paper we present a real-time adaptive filter for power-line interference suppression. The filter meets the IEC 60601-2-51 Standard requirements for diagnostic electrocardiographs with ringing noise < 25µV when QRS slopes are up to 60µV/ms. The filter can follow an amplitude change ratio as high as 2400 µV/s and a frequency change ratio as high as 0.15 Hz/s for 50 and 60 Hz mains interference.

**G8.9: Mudrov Ts, Krasteva V, Jekova I, Mudrov N, Matveev M, Stoyanov T. (2010) Device for data collection during cardioversion. *Annual Journal of Electronics*, vol. 4 (2), pp. 142-145, ISSN:1313-1842, Technical University – Sofia**

**Abstract**

This study presents a measurement system, named DEFIMPULSE Recorder, developed for collection of high-resolution data associated with the patient response during cardioversion. DEFIMPULSE Recorder acquires signals via the two ECG/defibrillator pads and provides: (i) recording of high-intensity voltage and current pulses during defibrillation shocks; (ii) long-term recording of ECG, high frequency impedance (baseline and variance). The correlation of this extended dataset with the patient diagnostic indicators is a powerful tool for statistical assessment of the optimal stimuli settings with improved efficacy of the treatment.

**G8.10: Mudrov N, Mudrov Ts, Dotsinsky I, Kostov J, Matveev M, Stoyanov T, Sotirova L. (2010) Benchmark device for testing digital electrocardiographs. *20th National Scientific Symposium with International participation “Metrology and Metrology Assurance 2010”,* 9-13 September, 2010, Sozopol, Bulgaria, pp. 425-432, (in Bulgarian).**

**Abstract**

Digital electrocardiographs (ECGs) are among the most widely used medical devices in healthcare, playing a crucial role in diagnosing cardiovascular and other health conditions. Consequently, the periodic verification of digital ECG parameters is essential to ensure accurate performance. While analog ECGs are tested in compliance with the REGULATION issued by the Ministry of Transport and Communications No. 239 from 24.10.2003, following the international metrological recommendation OIML R 90, these devices are becoming increasingly rare. This trend has highlighted the need for a new standard specifically designed to verify digital ECGs. The newly developed standard incorporates relevant sections from OIML R 90, which still apply to digital ECGs, alongside additional test signals from the IEC 60601-2-51 standard, which is aligned with European directives. This updated benchmark allows for a high degree of automation in the verification process. The test signal generation sequence has been optimized to perform necessary switching automatically, without operator intervention, except when specific parameters require manual inspection. A limited series of six devices was produced based on this new standard. These devices were calibrated and distributed to the regional units of the Bulgarian Institute of Metrology, where they are now used for verifying the performance of digital electrocardiographs.

**G8.11: Dotsinsky I, Stoyanov T, Mudrov Ts. (2013) Power-line frequency monitoring using component of the subtraction procedure for ECG processing. *Annual Journal of Electronics*, vol. 7, pp. 54-56, ISSN: 1314-0078, Technical University – Sofia.**

**Abstract**

The so called subtraction procedure eliminates the power-line interference from the electrocardiogram without affecting the useful signal spectrum around the power – line frequency. An approach of the procedure aimed to track the frequency variation is applied in this study for continuous frequency measurement of the electric power distribution.

**G8.12: Vassilev P, Stoyanov T. (2014) Note on isohesitant intuitionistic fuzzy sets. *Notes on Intuitionistic Fuzzy Sets*, vol. 20 (2), pp. 27-30, Zentralblatt MATH (Zbl 1396.03104),** https://ifigenia.org/wiki/Issue:Note_on_isohesitant_intuitionistic_fuzzy_sets.

**Abstract**

In the present paper, the class of all intuitionistic fuzzy sets defined over a universe set X, with the same hesitancy distribution is considered. Some properties and notions are defined and studied.

**G8.13: Vassilev, P, Stoyanov, T. (2016) On a new ordering between intuitionistic fuzzy pairs. 8th European Symposium on Computational Intelligence and Mathematics. Sofia (Bulgaria), October 5-8, 2016, pp. 77-80, ISBN:978-84-617-5119-8,** http://escim2016.uca.es/proceedings/

**Abstract**

In this paper we investigate orderings between intuitionistic fuzzy pairs and find some relationships between them. Our purpose is to establish a meaningful automated way to determine an object which best fits a given object, when this specific object is compared to all others and the result of this comparison is in the form of intuitionistic fuzzy pairs. Our idea is to obtain a way of comparison which may be used to identify potentially similar structures, texts, geometric patterns, which can later be processed by other methods to verify or discard this initial hypothesis.

**G8.14: Christov I, Neycheva T, Stoyanov, T, Dotsinsky I, Simov D. (2018) Processing and analysis of electrocardiographic signals. Journal of the Bulgarian Academy of Sciences, vol. 11 (4), pp. 11-19, ISSN: 0007-3989, Publishing House of BAS "Prof. Marin Drinov",** http://www.stil.bas.bg/journBAS/cont2018_4_BG.html

**Abstract**

1. *Dynamic low-pass filter for electromyographyc noise suppression in electrocardiograms:*
We have created a pseudo-real time low-pass filter, self-adjustable to the frequency spectra of the ECG waves. The filter is based on the approximation procedure of Savitzky–Golay with dynamic change in the cut-off frequency. The filter is implemented pseudo-real time (real-time with a certain delay). An additional option is the automatic on/off triggering, depending on the presence/absence of EMG noise. The analysis of the proposed filter shows that the lowfrequency components of the ECG (low-power P- and T-waves, PQ-, ST- and TP-segments) are filtered with a cut-off of 14 Hz, the high-power P- and T-waves are filtered with a cut-off frequency in the range of 20–30 Hz, and the high-frequency QRS complexes are filtered with cut-off frequency of 100-420 Hz. The suggested dynamic filter satisfies the conflicting requirements for a strong suppression of EMG noise and at the same time a maximal preservation of the ECG high-frequency components.
2. *ECG changes as risk markers in some physiological and pathological patient's settings::*
Changes in electrocardiogram (ECG) in different patient groups were measured and analysed in several settings:
– Changes in the 5-year study of aging.
– Changes provoked by diagnostic tests: Brugada syndrome and a standard stress test.
– Changes after bypass.
– Patients with kidney disease – changes during hemodialysis.
– Changes in diabetic patients.
Conclusion: The analyses of the ECG parameters and their change associated with aging, physiological tests and cardiac surgeries are strongly reliable risk markers for worsening of cardiac function and sudden cardiac death.

**G8.15: Stoyanov T. Computer based ECG system. *Annual of "Informatics" Section, Union of Scientists in Bulgaria,* vol. 10 (2019/2020), pp. 54-60, ISSN:1313–6852, Publishing House of the Union of Scientists in Bulgaria, (in Bulgarian).**

**Abstract**

A PC-based ECG recording system has been developed that synchronously receives signals from all electrodes through an additional isolated amplifier. The system effectively eliminates electrical interference and suppresses baseline drift, displaying the ECG signal in real time on the computer screen. The signals are continuously stored in the PC's memory during recording and are saved to the hard drive upon completion, enabling further processing and analysis.