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Research field: Bio-medical machine learning

Title: **Deep learning for real-time Fetal ECG monitoring**

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Abstract

Fetal ECG is the leading tool to analyze and detect abnormalities during fetal development. For example, to identify fetal distress and intrauterine hypoxia. Currently, the most common method to monitor a fetus, especially during labor is through fetal monitoring, which is based on auscultation, though there are more accurate methods, based on the electrical signal of the fetus (the fetal ECG or FECG). There are currently two methods for obtaining FECG. One is an invasive scalp electrode technique that is invasive and used during labor, while the other is based on electrode patches that are placed on the monther's abdomen to collect the signals. However, the signals from the maternal abdominal are highly noisy and include the mixture of maternal ECG and a weak FECG on top of maternal breath sound and increased level of noise. In practice the extraction of the FECG is done using long sampling cycles, with high computational cost and with limited success which depends on the magnitude of the fetal source. This is the most accurate method of objective fetal monitoring currently available, however, all electrical methods of acquiring a reliable fetal signal have not proven to be accurate.

In this work we propose a new approach to extract the FECG from the joined maternal-fetal data by sampling the joined ECG from at-least two sources and training a deep learning model to split the two in real-time. Since this is a hard task, we present a patient specific tailored **personalized self-supervised network.** This method is trained per patient (maternal and fetal) and can extract the maternal ECG in real-time and with high-quality. Based on preliminary results on real data, we demonstrate that the hypothesis and solution are applicable and feasible.

The Fetal monitoring market is increasing rapidly and accelerated after the recent pandemic. According to the insight partners market review, we accept to see a rise from $3.8b 2021 to $6.4b by 2028.

1. Introduction

An electrocardiogram (ECG) is a non-invasive test that records the electrical activity of the heart to assess its health and detect any abnormalities [1]. It is also used to monitor fetal heart activity during pregnancy to prevent neonatal morbidity and mortality [2][3]. During the test, electrodes are placed on the mother's thorax and abdomen, and an ECG machine records the reflected voltage changes produced by both the maternal and the fetal hearts as a mixture of signals. Although ECG tests are convenient and easy to perform, they can be challenging to analyze fetal ECG (FECG) signals because they are mixed with maternal ECG signals with much higher amplitudes, in addition to other sources of noise, including respiratory noise, muscle artifacts, electrode motion, or baseline wander [2]. Furthermore, the distinct morphological differences between these signals, such as the smaller amplitude and shorter cardiac cycle of FECG, can make it difficult to discern the FECG in the presence of the larger and slower cycle MECG, making it challenging to accurately analyze the raw FECG signals. Therefore, an effective process for extracting FECG signals is important and in demand [4].

2. Related work

There are several techniques in the literature for extracting FECG signals, including correlation techniques, matched filtering, wavelet transform, and Blind Source Separation (BSS).

An example of a classical signal processing approach is described in Lima Herrera et al. [5], which proposes the use of wavelet decomposition and an adaptive filter with the least mean square algorithm for noise cancellation to extract FECG signals. Another study by Ghaffari et al. [6] proposed a new method for selecting the best channel for detecting fetal QRS complexes from FECG signals, using a combination of geometric features and wavelet-based techniques. Among the techniques above, BSS tends to perform better than most of the other signal processing techniques [7]. In one study [2], the Joint BSS (JBSS) algorithm was evaluated for its effectiveness in separating the mixed signals, and it was found that the JBSS-CUM4 algorithm performed well for FECG extraction. In Zhongliang et al. [8] a comparison between artificial neural networks (ANN), BSS and adaptive filtering for separating FECG and MECG was conducted. The results showed that BSS techniques based on empirical mode decomposition (EMD) were the most effective in extracting FECG. Ramli et al. [9] also examined BSS techniques, specifically the Degenerate Unmixing Estimation Technique (DUET) algorithm, for extracting FECG in situations where the number of sources is greater than the number of mixtures, such as in the case of twins or triplets' pregnancies. Other studies employ Independent Component Analysis (ICA), a subtype of BSS techniques, to separate mixed signals. ICA is a computational method for decomposing a multivariate signal into its additive subcomponents. The authors in [10] studied the use of the FastICA algorithm with maternal R-peak suppression for FECG signal extraction, and [11] reported on an improved FastICA method that incorporated an over relaxation factor into Newton's iterative algorithm to process the initial weight vector randomly. This improved FastICA was able to separate the source component by selecting the best maternal MECG and removing it using singular value decomposition (SVD).

Deep learning approaches to FECG extraction were also useful for understanding the various preprocessing techniques and datasets used in the field and provided useful information when planning the current network. One example of a deep learning method is [12] by Fang-Wen et al., which uses the simulated PhysioNet [13] dataset to detect FECG peaks. However, this work only uses simulated data and does not perform a full BSS as intended in the current project.

All methods described above require high computational costs, long sampling and cannot perform real time separation of the signals. In this work we show for the first time that a personalized (per maternal-fetal) deep network can be trained to solve this task in real-time and is feasible to be the next generation baby monitoring.

3. Methods

3.1 Main idea

While deep learning has shown its superiority on probably any signal processing task it requires visibility to large amount of labeled data. Only in the problem we face the amount of data we poses is limited, hardly any labeled data exists, and the variance between different couples (mother and fetus) are substantial. For that we suggest to

- Train low layers of filters using simulated data (Figure 1: Encoder). We generate data and train **fully supervised**.
- Freeze the trained encoder.
- Construct two separate decoders for mother and fetus **using self-supervised cost function** on the summation (Figure 1: Decoders)
- Train the mother decoder to find only the gap from the thoracic pipeline and the joined pipeline.

The first training done on large amount of data, while the second self-supervised is done without the labeled data and conducted for a specific mother and fetus for about 30sec of data. After that we hold in our hands a **personal source separation network** that can extract the fetus ECG in real time out of the joined signal.

3.2 Suggested architecture

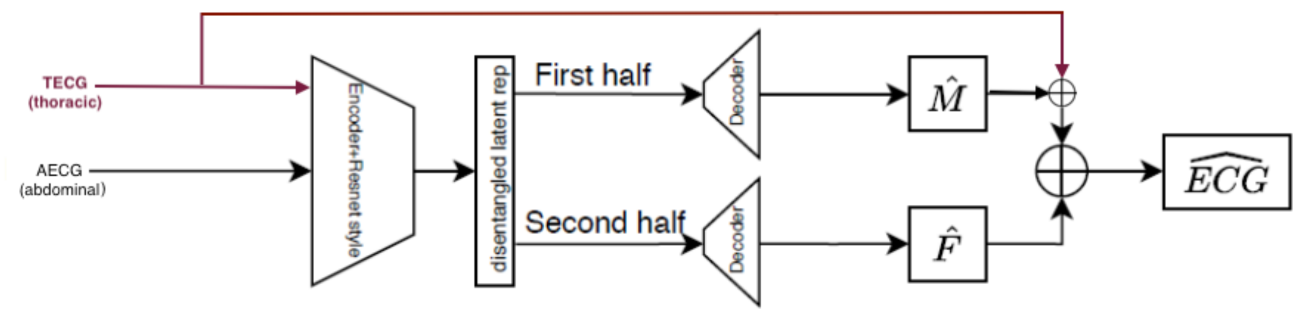

Figure 1: Proposed architecture. Two signals originated from two body locations on the mother. A mixed encoder processes the signals follows by a split into two decoders. We merge the first decoder with one of the signals (to learn a delta function) and join again with the second decoder. The outcome is mixture ECG that should match the joined source.

3.3 Data

3.3.2 Simulated data

After a deep and through research, the Fetal ECG Synthetic (FECGSyn) [14] database was chosen to be the simulated data for our model. This database is created by using the FECG simulator by Behar et al. [14]. The simulator simulates a 3D pregnant woman. In this model the maternal-fetal heart are punctual dipoles with different magnitudes and spatial positions so that maternal-fetal-noise signals can be treated as singular component. These individual sources propagate their signals towards observational point (electrodes) that are placed on the 3D model in different 34 positions (channels) on her abdomen. The dataset consists of 10 simulated pregnancies, with 6 different physiological events simulated for each pregnancy. For each event, there are 5 Signal-to-Noise Ratio (SNR) levels of additive noise. Each combination of event and noise level has 5 repetitions. Each signal has a duration of 5 minutes and a sampling rate of 250 Hz with 16-bit resolution. The dataset includes 3 signals (FECG, MECG, and Noise) that are provided separately. In order to get a standardized input size, the simulated data was also divided into windows of size 1024.

3.3.3 Real data

The Non-Invasive Fetal ECG Arrhythmia (NIFEA) [14] database was chosen to be the real-world data for our model. This database provides 12 fetal arrhythmias recordings and 14 normal rhythm recordings performed using the Non-Invasive Fetal ECG (NI-FECG) [15] technique. For each recording, a set of four or five abdominal channels and one chest maternal channel were recorded. The sampling frequency was 500 Hz or 1 kHz.

4. Preliminary results

5.1 Simulated ECG Data

Our model succeeds in an optimal and precise way to separate simulated ECG Data. The model was able to reconstruct correctly 94% of the overall datasets. The supervised setting helped to extract the critical features presents in both FECG and MECG. As shown in Figure 2, the model succeeds in both predicting the time positions, that it is the most important aspect of the signal, and the PQRST morphology.

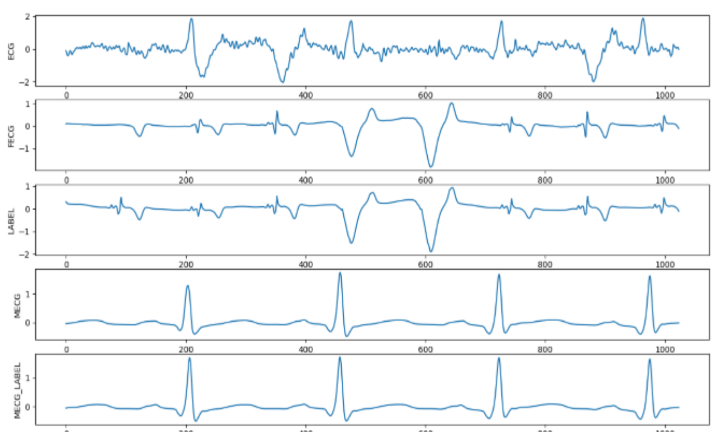

Figure 2: Source separation of ***simulated*** *joined ECG signal (first row), the extracted Fetal data (second row), the true (label) ECG (third row), the extracted maternal ECG (fourth row) and the true (label) maternal ECG (fifth row). Note different scale axes for maternal and fetal data.*

5.2 Real-World ECG Data

Our model was able to separate mixed ECG signals from the NIFEA database in multiple cases and noise levels. As shown in Figure 3, one key success of the model is its ability to accurately predict the time positions of the fetal ECG (FECG) signals, which is a crucial aspect of the project. In addition, the model was able to effectively process FECG signals with small amplitudes and not treat them as noise, which can be a common issue in these types of analyses. Furthermore, the model was able to reconstruct the majority of the PQRST morphology features of the FECG signals, which provide important information about the function of the fetal heart.

Please notice in Figure 3, that the extracted FECG signal has different y-axis scale due to a smaller amplitude, as expected and stretched for visual aid.

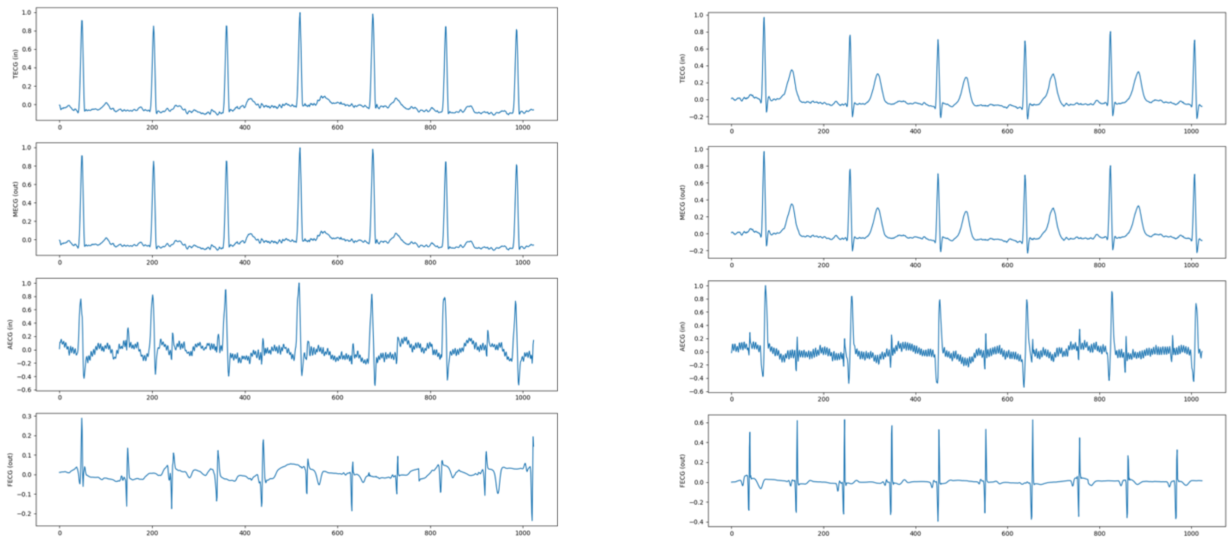

Figure 3: Source separation of ***real*** *joined ECG signals. First and Third rows are the joined sampling from two sources. Second row is the maternal ECG and Fourth is the Fetal ECG. Note different scale axes for maternal and fetal data.*

5. Objectives

Objective 1: Build a real-time ECG source separation deep learning code – improve preliminary results and experiment with different architectures and training models. **(Software only)**

Objective 2: Build an ECG baby monitor with the generated ECG split (following Obj 1 algorithm). **(Hardware and software)**

References

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Lecture Notes in Electrical Engineering, 269 (2019), pp. 3469-3474

[8] Dzati Athiar Ramli, Fong Mei Ling, Norsalina Hassan
"Degenerate unmixing estimation technique (DUET) for fetal ECG blind source separation."
Procedia Computer Science, 159 (2019), pp. 610-619

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[10] Li Yuan, Zhuhuang Zhou, Yanchao Yuan and Shuicai Wu. (2018) "An Improved FastICA method for fetal ECG Extraction." Computational and Mathematical Methods in Medicine 7061456: 1-7.

[11] "Deep Learning for Detection of Fetal ECG from Multi-Channel Abdominal Leads" 2018 – Fang-Wen et al.

[12] PhysioNet - Fetal ECG Synthetic Database. 127k samples which are sampled at 250Hz.

[13] "An ECG Simulator for Generating Maternal-Fetal Activity Mixtures on Abdominal ECG Recording" 2014 - Behar et al.

[14] Behar, J. A. et al. "Noninvasive fetal electrocardiography for the detection of fetal arrhythmias".39, 178–187, (2019).

[15] Goldberger A.L. Amaral L.A.N. Glass L. et al.: 'Physiobank, PhysioToolkit, and PhysioNet: components of a new research resource for complex physiologic signals', Circ. Electron. Pages, 2000, 101, (23), pp. e215–e220

Budget

Equipment

	Year 1
Cloud Computing resources	$20K

Personnel (including tuition)

	Year 1
PhD (150%)	$43K
MSc (150%)	$37K

Summary

	Year 1
Zimin	$75K
Matching from university	$25K

Budget justification

Today cutting-edge research in deep learning field requires computational resources and skilled personal.

Computing:

Deep neural networks average training takes between several days to several weeks on today's clusters. A local desktop per researcher allows us to get proof-of-concept but the final models must be trained on a mini-cluster. The pricing provided relates to a standard 8 GPU (Nvidia A3090 or higher) with 256Gb memory, and a dual Xeon processor with 16cores. Pricing refers to 3 months of training on university resources.

Personnel:

No research can be done without great students. I believe that students should be full time in the lab. The research should be the last thing they think when they go to sleep and the first think that goes through their head when they wake up. For that I need to be able to fully support my students. I wish to hire for this project one M.Sc. and one Ph.D. student. The request amount is the standard of CV/AI students in the campus.

Dan Raviv – CV

EDUCATION

Technion – Israel Institute of Technology

- **B.A.** in Mathematics and Computer Science — Mathematics Department — 2003-2006
  Summa Cum Laude
  Graduate of the **Technion Excellence Program**
- **M.Sc.** in Computer Science — Computer Science Department — 2006-2008
- **Ph.D.** in Computer Science — Computer Science Department — 2009-2012

Massachusetts Institute of Technology (MIT)

- Postdoctoral researcher — Media Lab / MIT — 2013-2016

ACADEMIC EXPERIANCE

B.A., Mathematics department, Technion — 2002-2006

Double major in Mathematics and Computer Science. Graduated top of my class

- Conducted research in the field of computer vision
- Characterized geometric groups from depth camera sensors
- Attendant monthly enrichment lectures by leaders from industry and academia, including novel laureates, given exclusively to members of the Technion's Excellence Program

M.Sc., Computer Science department, Technion — 2006-2008

Advisor: Prof. Ron Kimmel

Thesis: "Symmetries of non-rigid shapes"

- Conducted theoretical and applicative research at the interface between computer vision and non-rigid geometry using differential geometry tools.
- Defined and solved geometrical problems on intrinsic symmetries of non-rigid shapes

Ph.D., Computer Science department, Technion — 2009-2012

Advisor: Prof. Ron Kimmel

Thesis: "Invariants metrics for non-rigid shapes"

- Led theoretical research in the field of computer vision
- Defined a new class of random walks which are scale, equi-affine or affine invariant
- Guided undergraduate students in different projects
- Designed personalized infants inhalation masks based on the facial geometry

Postdoctoral studies, Media Lab, MIT — 2013-2016

Advisor: Prof. Ramesh Raskar

- Led multiple multidisciplinary experimental and theoretical research projects independently in the fields of computer vision, machine learning, and computational photography
- Developed new architectures for deep neural nets which encapsulate invariants as part of the training steps. Showed state of the art results for action (gestures) recognition
- Invited Plenary lecture in ALGORITHMY 2016
- Collaborated with leading industry companies on joint research topics, including smart-materials (Stratasys), simulations (AutoDesk), emotion sensing (YouTube), and big-data (Google)
- Collaborated with several medical facilities (MGH, Boston. Rambam, Israel. Carmel, Israel.)
- Mentored two M.Sc candidates, and four Ph.D. candidates in multiple projects
- Assisted and led several proposals and grants submissions
- Received the Biennial award from Society of Industrial and Applied Mathematics (SIAM) 2016
- Invited Speaker (prize lecture) in the SIAM annual meeting

ACTIVE PARTICIPATION IN SCIENTIFIC MEETINGS

- Workshop on Non-rigid Registration and Tracking. Rio de Janeiro, Brazil. Oral. 2007.
- Workshop on 3D Object Retrieval (3DOR). Firenze, Italy. Oral 2010.
- Proc. 3D Data Processing Visualization and Transmission (3DPVT). Paris, France. Oral. 2010.
- Outdoor and large-scale real world scene analysis workshop. Dagstuhl, Germany. **Invited speaker.** 2011
- Proc. IEEE Computer Vision and Pattern Recognition (CVPR). Colorado Springs, USA. Poster. 2011.
- Scale Space and Variational methods (SSVM). Ein-Gedi, Israel. Oral. 2011. Oral x 2. 2012. Oral.
- International Congress on Pediatric Pulmonology. Bangkok, Thailand. **Invited Speaker.** 2012.
- Proc. Eurographics workshop on 3D object retrieval (3DOR). Cagliari, Italy. 2012.
- Statistical atlases and computational modeling of the heart. Boston, USA. 2014.
- CLEO: Science and Innovations. San Jose, USA. 2014.
- Computational Optical Sensing and Imaging, Imaging and Applied Optics. CT3F4. Arlington, USA. 2015.
- ALOGITHMY, Conference on Scientific Computing. Podbanske, Slovakia. **Invited Speaker. Plenary.** 2016.
- BigVision, the 4th international workshop on large scale visual recognition and retrieval. Las Vegas, USA. Oral. 2016.
- Siam Conference on Imaging Science. Albuquerque, USA. 2016. **Invited speaker, Prize lecture.** 2016.
- From non-rigid to null space. IPAM, UCLA, USA. Oral. **Invited Speaker**. 2019.
- Avatar (autonomous driving) consortium. 2021.
- Israel smart transportation initiative. 2021.
- MICCAI learn to erg challenge. 2021.
- Apple. **Invited Speaker**.2023.

ACADEMIC AND PROFESSIONAL AWARDS

<u>Fellowships/prizes</u>

• **President's / Dean's list** for academic achievements for every semester of undergraduate studies	2003-2006
• Technion Graduate School excellence scholarship	2006
• B.A., **Summa cum laude**	2006
• **Graduate of the Technion's Excellence program**	2006
• **Gutwirth** fellowship for **excellence in research**	2009/2012
• Intel prize for **excellence in research**	2009/2012
• **Excellence in research award,** Computer Science department, Technion	2006/2012
• MIT-Technion **post-doctoral fellowship**	2013
• Biennial award from Society of Industrial and Applied Mathematics SIAG on Imaging Science **best paper** prize	2016

<u>Teaching</u>

• Excellence in teaching award, Computer Science department	2006/2008
• Technion's excellence award for lecturers, Computer Science department	2009/2011
• Technion management prize for **outstanding adjunct teachers**	2012

MILITARY SERVICE

- Served as a helicopter pilot in the Israeli Air-Force (IAF)
- Rank on completion of service – Major
- Received the Department Award for my role as a group leading officer

January 08, 2023

The Zimin Institute for Engineering Solutions

Dear committee members,

It is my great pleasure to provide my endorsement for Dr. Dan Raviv for The Zimin Institute 2023 grant in bioengineering. Dan holds a tenure-track position as a Senior Lecturer at the School of Electrical Engineering at Tel-Aviv University. He joined our department after spending 4 years at MIT, where he worked as a postdoc on cutting edge problems in the field of Machine Learning, Computer Vision, and Geometry. He is an expert in geometric deep learning on high-dimensional data and is well known and appreciated by his peers. He has an impressive publication record of more than 45 journals and peer-reviewed conferences as well as several book chapters.

In his short academic career, Dan has been an invited speaker on multiple occasions, and received the prestigious SIAM biennial award for Imaging Sciences, granted to top scientists in his field.

Since Dan joined the School of Electrical Engineering, he has established a strong research group composed of ten graduate student and he is sought-after advisor. He is working closely with multiple companies and medical centers and knows how to leverage his work also for industry needs. He participated in two industry-supported consortia in autonomous driving and soft robotics, securing $500K in research funds, and currently part of a new smart-material initiative.

Dan's ambition to use Machine Learning techniques for biomedical problems is highly promising. I find the suggested project original and innovative, and I am confident it will lead to a long-term impactful research program in his lab.

Given the above, I highly recommend Dan and his project for funding by the Zimin institute.

Best regards,
Rami

Rami Zamir, Professor
Head of the School of Electrical Engineering
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SHEBA
Tel HaShomer
City of Health

25 Jan 2023

Dear Zimin Foundation

I hereby confirm my ongoing research with Dr. Dan Raviv for building the next generation ECG fetal monitoring. The fetal ECG (FECG) **reflects the electrophysiological activity of the fetal heart**. Using FECG waveform analysis, fetal abnormal heart rates, such as fetal arrhythmias or abnormal cardiac rhythm which may reflect fetal distress and intrauterine hypoxia, may be detected and treated apropriatly. Today traditional fetal monitoring tools are limited yet practical for pre-birth examination, including the maternal monitor which uses old fashion auscultation for real time monitoring. We are eager to replace the current method with FECG monitor as it may become a much easier, more accurate and reliable method for analysis both in the hospital and in community practice. As the there is no easy solution for separating the joined maternal-fetal signal, extracted today from the abdominal ECG monitors, the work done in Dr. Raviv's lab may show great potential in revolutionizing the pre-birth monitoring, allow much wider fetal observation and thus save lives and reduce costs as the monitoring may be performed in early stages by the community healthcare provider. As head of the medical device Hub in the Sheba ARC innovation center I value the transformation this tool can make in large communities helping reducing the visits to the maternity emergency departments in one hand and detecting real fetal distress on the other – reducing undetected fetal stress.

Shai Tejman-Yarden, M.D.

Dr. Taejman-Yarden graduated from the Hebrew University Medical School in 1995 and Joined the IDF Air force, later to become a base clinic commander. As part of his military service he joined the pediatric service in Soroka University Medical Center where he completed his residency in 2007. In 2012 he completed his fellowship in Pediatric cardiology and Electrophysiology in UC San Diego CA and started serving as an attending physician In the Edmund and Lily Safra Congenital Heart Center in Sheba Medical Center. In 2008 Dr. Tejman-Yarden completed a Masters degree in BioMedical Engineering in Ben Gurion University. Since 2015 heads the lab for Engineering Medical Research in the Safra Cong. Heart Center leading research in various fields of biomedical engineering. Dr. Tajmen-Yarden dual expertise in engineering and medicine put him in the direct track to understand the needs, limitation and optional solutions that appear in the intersection between medical care and modern technological tools. In 2022 Shai was invited to Join the ARC innovation center as the head of the Medical Device Hub, responsible for assisting the Sheba inventors martialize their dreams in this field.

Shai

Shai Tejman-Yarden MD MSc MBA
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