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Remote monitoring and prognosis of the development of atherosclerotic plaque based on IoT and Cloud Computing

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Abstract

Our goal in this paper is to explore the innovative applications of the Internet of Things and Cloud Computing in the intelligent analysis of human health related data. The targeted application is the remote monitoring of the development and progression of atherosclerotic plaque in the coronary aortas of the heart muscle using small, wearable, sensors based on the Doppler shift effect and the use of electromagnetic/optical signaling. The innovative element of our approach is that we propose to monitor the progression of the atherosclerotic plaque, which gradually leads to more and more narrowing in the arteries at the point of deposition of the atheromatous material, by measuring the volume of the aorta as well as the blood flow rate. Arterial volume and blood flow measurements are captured by specialized sensors as well as wearable IoT devices and are communicated to Cloud-based applications for processing and intelligent analysis. Remote monitoring of patients can result in early detection of atherosclerosis as well as provide a channel for accumulating (anonymously) large volumes of health-related data which can help professionals and policy makers in improving health care.

1. Introduction

The term Internet of Things (IoT) was coined by Kevin Ashton in 1999, who is one of the founders of the MIT Auto-ID Laboratory.

In particular, Ashton presented an innovative proposal to the company Procter & Gamblewhere he worked for on how to connect various objects on the Internet via an RFID tag (Radio Frequency Identification). The idea was that computing devices and the Internet are completely dependent on human related data and information. Therefore, if small computing components are dispersed in the environment that have their own means of collecting information and measuring parameters pertaining to the environment, it would be possible to detect and measure everything, anywhere (see [5]).

Almost twenty years later, Ashton's vision has come true and may have, even, exceeded his expectations. The IoT is now here, around us, above us, but also within us. Tiny sensors and devices surround us or are attached to us and follow us at every step. These devices sense and interact with the environment we inhabit and roam and collect related data which are, then, gathered and processed powerful Cloud Computing systems. These are web-based computer systems that form the, so called, Cloud and provide intelligent data and information processing applications based on Computational and Artificial Intelligence as well as Machine Learning, among other application domains, with the goal of extracting and processing useful information about us and our environment, improving the quality of life.

Specifically for the health sector, which is our target, before the Internet of Things era, patients' interactions with doctors were limited to face-to-face visits to the doctor's office or hospitals as well as consultation over the telephone. It was not possible for health specialist to monitor, on a regular basis, patients' health, especially during the (usually long) intervals between consecutive visits. In addition, in a long term, it was very difficult to share all this volume of health related data (suitably anonymized of course) of a country's population with experts as well as with those responsible for formulating the country's health policy for the immediate and distant future. Thus, valuable health related information, such as the long-term development of cardiovascular disease causes and indicators (e.g. blood pressure, arrhythmias, coronary artery stenosis), diagnoses, and correlations among all general population health information (e.g. evolution of population biomarkers, prescriptions and medication) was lost forever or remained inaccessible in a physician's office or computer.

In contrast, IoT devices have made it possible for people to interact remotely with health services, their physicians and the health care system, all this in real time without disrupting their daily lives. For instance, in the health monitoring domain, wearable or implantable medical sensors on or in patients' bodies constantly transmit health related data and biomarkers which, after intelligent processing by powerful cloud computing applications, facilitate the health system to provide people with more opportunities for disease prevention and access to health services. Moreover, the massive health related data collected by IoT devices can help physicians enhance their knowledge about symptoms and diseases, enabling them to identify, more effectively, the best treatment process for patients and achieve the expected results. This is because these data, in essence, sample biomarkers and health status information from large numbers of people dispersed globally on a continuous basis and, therefore, the physicians can forms a more complete and accurate picture of a patient's condition complementary, of course, to the absolutely necessary, but less frequent, face-to-face consultation sessions.

A generic cloud infrastructure processes data in four stages, as seen in Fig. 1 (see, for more details, [1] and [6]):

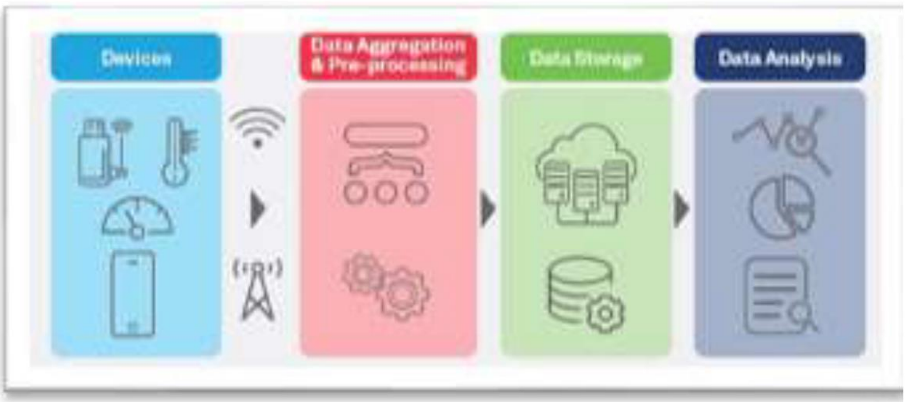

Figure 1: A four stage IoT Architecture for capturing, storing, and intelligently processing health data

- Step 1: The first step is to install suitable IoT devices in the targeted environment which include sensors of all types (in our application, medical sensors) and processing elements that collect and pre-process sensor data before sending them on the Cloud infrastructure for further processing and analysis.
- Step 2: Usually, the data received from sensors and other devices is in some raw format (e.g. binary or text) or a more structured standard format (e.g. JSON) and contain some measurements of a specific quality of the environment or health related biomarker (e.g. blood pressure or temperature) of patients. The data may be subjected to a preprocessing and "sanitization" phase so that they become suitable for the required further, intelligent, processing.
- Step 3: The data is then stored on secure massive storage infrastructures on the Cloud which are called data centers or data silos. The aim is to keep them safe, to the maximum possible degree, in accordance to the European regulatory framework for the protection of personal data GDPR.
- Stage 4: The management and analysis of the final data is performed by advanced methods of data analysis based on a wide range of techniques, including statistical analysis, Artificial Intelligent and Deep Learning.

Through the proposed approach in this paper, we aim to explore the innovative applications of the Internet of Things and Cloud Computing in the domain of intelligent medical data analysis collected from people using specialized sensors.

More specifically, our main goal is the remote monitoring of the development and progression of atherosclerotic plaque in the coronary aortas of the heart muscle in volunteer patients using small, wearable sensors based on the Doppler displacement effect and the use of electromagnetic/optical waves. The atherosclerotic plaque, which leads to a gradual narrowing of the arteries at the point of deposition of atherosclerotic material, can have serious health complications for the patient which range from mild stroke to, even, death.

The innovative element of our approach is that we propose the remote monitoring of the development of atherosclerotic plaque through the measurement of the aorta's physical properties and interaction with flowing blood. Such measurements include the velocity of the blood flow as well as the stenosis effects as a function of the plaque thickness. These measurements are performed on a continuous bases and over long time periods from specialized wearable sensors. The measurements, then, will be transmitted to the Cloud for intdepth processing and extraction of useful information not only for specific patients but for large numbers of them so that the health policy authorities can draw conclusions about the course of the health of a whole population.

In addition to our main goal, some individual goals that can be pursued are the following:

- Collecting large volumes of heart related data coming from volunteers with the aim of creating a completely anonymous database of shared health data (Civic Data) collected in real time without disrupting people's daily lives.
- Exploring the possibilities and limitations of the Internet of Things technologies in the demanding field of Medical Applications and, in particular, in the secure and safe remote collection and analysis of patients' health data in real time.

- Investigating the characteristics and effectiveness of lowcost, tiny and small wearable medical sensor devices in collecting reliable medical data with emphasis on data from the heart muscle and the significant difficulties that exist in the process.
- Utilizing the potential of the National Governmental Cloud infrastructure in Greece to interact with health-related databases (electronic prescription and electronic patient records) and to use intelligent data analysis applications from a private or national Internet of Things platform in to explore the correlation of the heart disease related data with the general picture of the patients' health in order to draw useful conclusions about the current and potential future status of population health, at least for cardiovascular condition.
- The development of an expandable, low-cost, Governmentbased infrastructure on the G-Cloud of the Ministry of Digital Governance for the monitoring of biomarkers of the population (volunteers) and provision of telemedicine services to needy citizens.
- At the same time, due to the enactment of the GDPR regulatory framework, an important goal is that all applications that handle personal data (sensitive or not) must protect them and inform data subjects about the use of this data (see the relevant legislation here [3]). Of course, the protection of this data and informing the subjects should always be the obligation of the service providers regardless of the regulatory framework, but with enactment of the GDPR, this obligation is imposed through a European regulatory framework. Therefore, the application should include strong mechanisms for the protection of moving personal data and be based on voluntary participation on the principle of consent.

We would like to emphasize that it is absolutely impossible for an automated system, like the one proposed in this paper, to replace humans and, in particular, the health specialist. The doctor's experience, knowledge, sympathy, and care for her/his patients cannot be replaced by any automated system, regardless of how advanced it is. The proposed approach aims, only, to gather and offer a large volume of data to the health specialists and health policy makers so as to enable timely intervention and action for individuals as well as population groups whose cardiovascular biomarkers are deteriorating over time.

2. The proposed approach

In our approach we focus on exploiting the potential of the IoT and the Cloud for the remote monitoring of health and the collection of biomarkers related to cardiovascular diseases.

There were two reasons behind this choice: (i) The increase in the number of cardiovascular diseases in our country (and globally) as well as the need to develop a large database of data related to these diseases and the evolution of related biomarkers, and (ii) Cardiology poses significant challenges for the capabilities and use of related sensor devices as well as data collection and transmission.

Especially for the second reason, the heart is at a position where it is difficult to attach and stabilize wearable sensors over a long time period while it is possible that patient may feel uncomfortable with the device attached near the heart area. In addition, heart-related biomarkers are complex (e.g., heart rate and pulse waveforms, intensity of heart muscle contractions etc.), often noisy, requiring very detailed and detailed processing (usually spectrum calculation and application of noise removal filters) for and quality improvement. For this reason, we chose

Cardiology as the target medical domain with emphasis on the monitoring of biomarkers related to atherosclerosis. The main goal is to correlate the volume of the vessels of the heart muscle and the coronary aorta with the development of atherosclerotic plaque over a long time period. In addition, the aim is to estimate how long the atherosclerotic plaque may take in order to become sufficiently large to endanger life as well as to correlate the development of atherosclerotic plaque with all human medical data available from public health services. Such data include, for example, electronic prescriptions of medicines and electronic health records of patients.

The idea we propose is the volumetric measurement of the coronary aortas in order to detect changes in their volume, during the pumping of blood from the heart muscle. The development of atherosclerotic plaque makes it difficult for the arteries to push blood, causing them to dilate, possibly more intensely (thus increasing their volume) over time and as the atherosclerotic plaque develops and obstructs the smooth flow of blood. More specifically, in Subsection 2.1 we briefly describe the process of atherosclerotic plaque formation and how its presence can be detected using sensors measuring the volume of arteries and vessels. In Subsections 2.2 and 2.3 we describe two types of sensors that we can use for this purpose while in Subsection 2.4 we propose a general IoT and Cloud Computing architecture for the collection, storage and intelligent processing of cardiovascular data received such sensors.

1.1 The process of development of atherosclerotic plaque and two phenomena (biomarkers) associated with it

Long term cardiology research has discovered that coronary heart disease begins with injury or damage to the inner layer of a coronary artery. This injury can occur even at a young age. At the site of the lesion, a layer of components, the atherosclerotic plaque, gradually forms on the inner surface of the coronary arteries, as shown in Fig. 2. These components, which are the atherosclerotic material, are often transported with the bloodstream from a very young age. Atherosclerotic material is a malleable and fatty material composed of inflammatory cells and lipoproteins (e.g. LDL cholesterol) which, however, over time becomes stiff and harder through the process of calcium deposition.

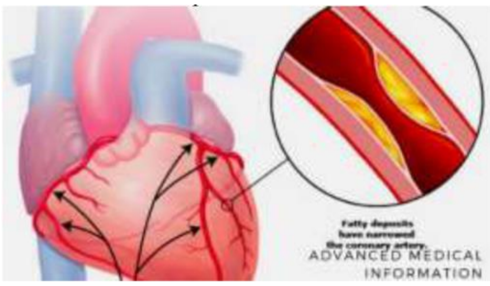

Figure 2: Development of atherosclerotic plaque in the coronary aorta

The development and hardening of the atherosclerotic plaque, following the process outlined above, essentially "shrinks" the lumen of the arteries and, consequently, leads to a reduction in the blood supply to the heart muscle. This may lead to the risky medical condition called myocardial ischemia. Over time, however, an affected coronary artery can lead to the development of new blood vessels that circumvent the blocked area so that blood flow to the heart muscle can be restored smoothly. However, these new vessels may not be wide enough to carry oxygen-rich blood at a satisfactory flow rate, leading to significant complications due to a lack (or even disruption) of oxygen to the heart muscle.

As we observe in Fig. 2, the development of atherosclerotic plaque creates a narrowing in the aorta resulting in difficulty in passing blood from the site where it has formed. This results in the occurrence of two phenomena, which are central to monitoring the development of atherosclerotic plaque: (a) a large deviation of the volume of the artery at the point before the atherosclerotic plaque through which blood flows, due to the pressure that blood exerts as a result of the difficulty of passing through the stenosis – this leads to a greater dilation of the aorta and, most likely, at greater increase of the volume of the aorta just before the site atherosclerotic plaque (b) at the point where blood flow through the atherosclerotic plaque, a change in blood flow velocity can occur due to passage of blood from a position of higher volume through a position of lower volume (stenosis) - this is the Bernoulli effect in fluid mechanics. In Subsections 2.2 and 2.3 we report some information on these two phenomena and how we can monitor them with appropriate sensors in order to draw useful conclusions about the development of the atherosclerotic plaque.

In general, by taking many daily measurements of arterial volume as well as the patient's blood flow rate over a relatively long period of time, we can draw valuable conclusions for the patient with respect to how fast atherosclerosis progresses. Such findings, over a large population, can help physicians and policy makers reach more substantiated decision with respect to patients' health and public health policies.

1.2 Detection of narrowing of arteries and vessels based on sensors measuring their volume changes

As shown in Fig. 3, volume change sensors are based on the use of optical waves to estimate the intensity of heartbeat. This estimate is based on measuring the changes in the volume of a blood vessel when blood is pumped by the heart muscle.

The proposed optical sensor is the BH1790GLC of ROHM Semiconductors that we chose for the proposed application, without excluding the use of an equivalent alternative sensor.

Figure 3: Optical wave based blood flow sensor

More specifically, an optical heart rate sensor measures optical waves whose reflection properties reveal changes in the volume of blood vessels due to fluctuations in the light intensity as emitted by a LED (Light Emitting Diode - green in this sensor). The adoption of an optical filter optimized for the detection of optical waves incident on the reflected optical wave sensor minimizes the effects of ambient light, such as red and infrared light. This allows the capture of high quality pulse signals, even outdoors.

1.3 Detection of arterial and vascular stenosis based on Doppler displacement measurement due to blood flow velocity

The application of the Doppler Effect to the measurement of blood flow rate is based on the Bernoulli Principle in Fluid Mechanics. As we see in Fig. 4 as the fluid flows from a conduit or vessel (in our application) from a larger diameter to a smaller diameter, the flow velocity momentarily increases and the pressure decreases so that the same volume of fluid is allowed to pass through the narrower region. Therefore, the velocity of blood flowing through the narrowing regions due to the presence of atherosclerotic plaque is expected to be higher than that of the blood flowing in the vascular regions on either side of the stenosis (see work [0]).

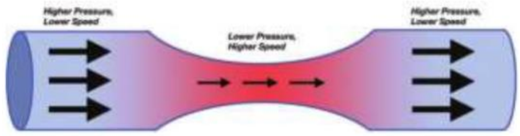

Figure 4: The Bernoulli Principle from Fluid Mechanics

The Doppler displacement effect can be applied to detect stenosis in a blood vessel or artery by measuring the velocity of blood flow and the velocity changes over time. Consequently, measuring blood flow velocity may indicate a difficulty in flow due to a narrowing in the vessel or artery, possibly due to atherosclerotic plaque formation.

The Doppler Effect technique can be visualized on the lefthand side of Fig. 5, where the waves emitted from a source at a certain base frequency (fo) are reflected by the moving red blood cells back to the receiver of the reflected waves at a higher or lower, generally, frequency (fr). The difference in these frequencies, known as the Doppler shift, can be used to calculate blood flow velocity (V) and flow direction. The parameter θ is known and set accordingly (see [0] for indicative values depending on the type of measurement) based on the angle between the incident beam and the direction of blood flow (essentially, the direction of the vessel).

The principle of operation of a Doppler Effect sensors is shown on the right-hand side of Fig. 5. More specifically, a laser emitting diode and a photodiode receiver (which is a photosensitive semiconductor) are installed on the Doppler sensor head. Infrared light from the laser diode is emitted to the skin, passing through it and reaching the vessel where it falls on the moving red blood cells and is reflected backwards. The reflected light is then detected by the photodiode. This results in a frequency shift that is proportional to the velocity of the moving red blood cells. It is therefore possible to obtain information on blood flow by analyzing the frequency spectrum of the detected signal in a specialized signal processing (e.g. available on the Cloud).

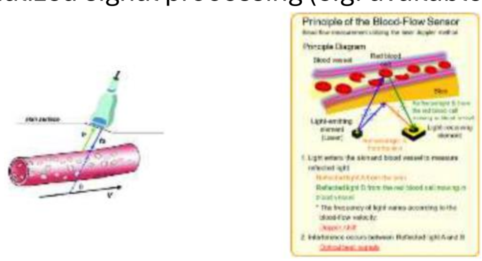

Figure 5: Doppler shift principle (left) in blood flow rate measurement (right)

In Fig. 6, on the left-hand side, we see a tiny Doppler Effect sensor from Kyocera that was proposed a few years ago. This sensor is based on a laser diode and a photodiode, as described above, which are integrated in a single ceramic package. This sensor is only one millimeter high, 1.6 mm long and 3.2 mm wide, so it is ideal for remote monitoring of the patient's vascular condition due to its wearability properties, for example, worn in a garment and in a position where the aortas of the heart are located. We believe that how and where the sensor will be placed on a patient’s body so as to receive reliable measurements at a minimal patient discomfort is a major challenge.

Also, on the right-hand side of Fig. 6, we see a more practical but, still, in a rather experimental stage, solution of a Doppler Effect sensor that is attached to the point of measurement so that it does not move and is constantly close to the desired point, thus providing more accurate measurements.

Figure 6: Wearable blood flow sensors based on the Doppler Effect

Possible applications of this type of sensors, which produce measurements of blood flow rate in blood vessels, include monitoring stress levels, preventing dehydration, heatstroke and high altitude sickness. All of these conditions can cause changes in the volume of blood flow in blood vessels that can be captured by Doppler Effect sensors and detected by suitable applications.

1.4 The overall system: collecting data from the heart muscle and processing it on the Cloud

In Fig. 7 we see a high level diagram of the proposed application architecture. As we can see, the main characteristic is the “open-hardware” IoT device shown in the center. This device acts as an intermediary between the sensor devices located on the human body (such as blood flow and artery volume sensors) and the Cloud based intelligent analysis applications. These applications, in turn, analyze the continuous flow of heart related data, in real time, in order to extract useful information about the condition of the arteries of the patient carrying the sensors and the IoT device.

Figure 7: The generic IoT/Cloud architecture

In general, are there many intelligent data analysis techniques available on a typical Cloud Infrastructure (in our case Greek government cloud G-cloud and its in-house or licensed services). This include Artificial Intelligence (AI) methods, Machine learning, Regression Analysis, Neural Networks, Semantic Networks etc. In particular, the following three tasks, we believe, can be particularly useful in drawing conclusions from the collected data, as well as creating predictions for the progress of atherosclerotic plaque individually for each patient and in the general population:

- Correlation (with statistical methods) of arterial volume and blood flow velocity data with the medical data about the progress of atherosclerotic plaque in a population. In essence, this investigation will demonstrate how important arterial volume and blood flow rate are as biomarkers for the prognosis of atherosclerosis. The large amount of data that will be extracted with the proposed architecture can contribute significantly to the accuracy of the correlation results.
- Creation of arterial volume and flow velocity change plots and histogram with the aim of visually correlating these two biomarkers and subsequently subjecting them to correlation and variability analysis in order to identify any influence on each other, in the long run, with respect to atherosclerosis.
- Correlation of the data received from the sensors with data kept about patients in the Public Administration systems and, in particular the electronic health records. The aim is to investigate whether arterial volume and blood flow rate are accurate predictive biomarkers of a patient's health.
- Decision to send a warning to health units or treating physicians if the arterial volume and data flow rate measurements deteriorate, indicating a dangerous increase in the size of the atherosclerotic plaque.

Certainly, experts in medical research and data analytics can apply several data analysis methods, once sensor data are captured, in order to draw useful health related information. The critical issue, we believe, is that through the proposed system, large volumes of such data can be archived and processed which would be, otherwise, unavailable if only face-to-face consultations took place.

3. Conclusions and further actions

In the present paper, we have proposed an architecture for continuous remote, monitoring of the development of atherosclerotic plaque, through arterial volume and blood flow rate sensors and Cloud-based processing.

Our vision is that the gradual narrowing of the aortas will be reflected in their volume as well as the speed of blood flow due to the pressure exerted on the blood at the point of narrowing. This hypothesis may be of interest to independent investigation in addition to being a key element of the proposed system. An important parameter, but also a difficulty of the system, is the way the sensor subsystem is attached on the patient's body as well as the way the sensors are attached near the heart muscle and close to some of the coronary arteries. Generally, in Internet of Things applications in Medical Science one of the most crucial points is how to achieve, with the least possible discomfort, the contact of the sensors with the patient's body. We believe that with a little experimentation and training of the patient (always on a volunteer bases) this difficulty can be resolved.

Also, an important aspect of our proposal is to investigate the possible correlation of the two biomarkers on which the monitoring of the development of atherosclerotic plaque is based, i.e. the volume change of the aorta and the change in blood flow rate due to the development of the atherosclerotic plaque. The proposed system can help to investigate this correlation as well as the correlation of any set of biomarkers related to the development of atherosclerosis.

Of course, the proposed approach by no means is meant to replace conventional health services as well as face-to-face consultations with physicians. No automated system can accomplish this, now and in the future, in our opinion. However, the technological advances have resulted in powerful sensor and computing devices which can be the remote “eyes” and “ears” of physicians over their patients. In many cases, these technologies can help to identify risky situations for people and, consequently, help them seek timely medical help.

The proposed approach can help enhance the ability to collect and intelligently process citizens' health data, which in combination with existing electronic medicine prescription data and patients’ health records, can lead to valuable conclusions about the general health and biomarkers accuracy in all fields of medicine.

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