DEVELOPMENT OF A DETECTOR OF HEART MURMURS

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ABSTRACT

The most common cardiac afflictions are the heart murmurs, which are defined as abnormal noises during cardiac cycles. These abnormal noises are symptoms of a variety of cardiac pathologies, some of which can become very serious and put at risk the life of a person. Nowadays, heart murmurs can be precisely detected just by the combination of advanced equipment and a specialist physician. However, these resources are costly and scarce. Faced with this reality, is that the need for a low-cost and easy-to-use medical device that helps non-specialists improve their ability to detect and diagnose heart murmurs was identified. This investigation presents a prototype design proposal for a medical device, that would give capability to record, analyze and provide the first diagnosis of most common heart valve pathologies.

The design proposal was evaluated by a functional diagnostic test, using a simulator programed by computer. The results obtained show a sensitivity of 91.7% and a specificity of 82.6%, which are acceptable results compared to assessments made by other researchers of the topic.

It is concluded that the algorithm works properly during the initial assessment; however, it is required to perform additional evaluations with a larger sample of heart sound records, in order to achieve better statistical determination of configuration parameters.

Keywords: Heart, Murmur detector, diagnostic, device.

1. Introduction

The heart murmur is a condition that manifests itself as an abnormal noise in the cardiac activity, which is the result of a turbulent flow of blood through the heart valves [1]. In most cases, these abnormal noises do not pose a risk to the health of the patient [2]. However, in other case, they represent a serious danger to life and could lead to heart failure or blockage of arteries in the brain due to blood clots [3]. The diagnosing of these deficiencies of cardiac function is performed today by medical auscultation using a stethoscope, with a well-trained physician who can differentiate between normal and abnormal sounds of blood flow through the heart valves during the contraction and relaxation of the heart [4]. Nevertheless, this diagnosis is preliminary and usually if the result is positive for the existence of a murmur, it is required to continue with more complex studies to determine the anatomical failure, which have the disadvantage of being more complex and costly [2]. The need is highlighted here, then, to have a simple, practical, economical and effective way to detect such types of defects in the cardiac function, so that it is available to the population in a convenient manner at places of primary medical care [5].

In this research the design of a medical device for detection and diagnosis of heart murmurs is proposed by the registry (Phonocardiogram) and sound analysis of the cardiac activity [6].

To conduct such research, the current progress on the issue that researchers from several countries have carried out was reviewed. The most important results are shown, along with the methods by which the major technical challenges have been faced [5]. On the other hand, a systematic methodology followed to reach the final proposal for the design of the device was performed, counting with the help of eight staff physicians for the partial functional test of the algorithm.

Finally, the development and implementation of a computer simulator programmed in LabView to test, the functional algorithm is shown. Likewise, the results of the functional test performed with the medical staff are shown and the initial results of concordance, sensitivity and specificity of the device are discussed; as well as proposed conclusions and recommendations for future progress on the issue by other researchers.

2. Materials and Methods

Initially a research on the literature was conducted on reports that researchers in the field have published, and an assessment was done to establish the current offer in the market of related devices. Next, several proposals for a new design of a medical device for detection and diagnosis of heart murmurs were analyzed. The proposals were analyzed according to a table of positive and negative aspects of each. This methodology helped to choose the best proposal to be developed. Some of the aspects that had to be defined were: (1) dimensions of the device, (2) algorithm of classification and diagnosis of the cardiac sound (3) sound detection transducers and (4) external framework and interface.

After selecting the best proposal for the design of the medical device, an algorithm was designed using LabView™ (National Instruments) installed on a personal computer. With the programming in this language it was possible to evaluate some of the criteria for classification and diagnosis. This software was based on the analysis of the signal amplitude to provide diagnosis, unlike those created before, in which the most important characteristics of sound that have been analyzed were the intensity and frequency of their harmonicas.

The efficiency of the program was evaluated by analyzing heart sounds previously recorded and diagnosed, taken from the literature [7,8]. Sounds obtained were both from healthy people as well as patients with valvular dysfunction. The evaluation of the algorithm was performed using a statistical study of concordance by attributes.

For this study, the collaboration of 8 medical professionals was requested, who, together with the use of a computer with the algorithm for murmur detection, performed the diagnosis of 3 samples of phonocardiograms, with 3 repetitions each random sample. Neither the doctors nor the system programmed with the algorithm had access to the information about the confirmed diagnoses of the samples.

With this evaluation, the consistency and accuracy that a doctor may have to use the simulator for detection of murmurs, as support for an effective diagnosis was determined.
Selected audio samples have the following confirmed diagnoses, according to Table 1.

Table 1: Types of Phonocardiogram chosen to study efficiency of algorithm. Source: Authors

Phonocardiogram diagnosed
Normal Heart
Pulmonary Regurgitation
Regurgitation Tricuspid

To sum up, the outline of the study was that each evaluator conducted 9 diagnostic samples. The order in which the sound was presented to the evaluator to be diagnosed was randomized and the evaluator had no knowledge neither the order nor the true diagnosis of each case.

The concordance levels of diagnostics collected were evaluated by calculating the Kappa statistical index which represents the level of concordance of the classification of an evaluator compared to itself, with the reference value. The value of this indicator is between -1 and 1. Table 2 shows the interpretation of the indicator values.
In this research a Kappa value of 0.75 or more is considered as a good concordance value.

Besides the statistical index Kappa, sensitivity and specificity indicators were also calculated, which are widely used by researchers in the field, to determine the effectiveness of murmur diagnostic algorithms. This indicators were used in order to have a standardized measure of effectiveness that allows comparing the performance of the algorithm presented here with others developed previously.

Table 2. Interpretation of statistical Kappa. Source: Authors

Kappa statistic value	Interpretation
1	Total concordance
0	50% concordance
- 1	No concordance

These indicators are percentages and they are calculated as follows:

$$\text{Sensitivity} = \frac{tp}{(tp+fn)} \quad (1)$$

$$\text{Specificity} = \frac{tn}{(tn+fp)} \quad (2)$$

Source: Voss et al. 2005

Where *tp* is the number of true positives, *tn* the number of true negatives, *fp* the number of false positives and *fn* the number of false negatives.

A phonocardiogram will be classified as a murmur if it presents amplitudes of the signal above a comparison value in systole and diastole. In all cases, the simulation was able to detect the noises added to the systole and diastole, being able to detect the presence of a heart murmur. The comparison value chosen for systole and diastole was 0.35 of amplitude. The following report includes the full statistical analysis of the test of the efficiency of the algorithm as well as conclusions and recommendations of the research team for future advances in the field.

Results and Discussion

Development of the external physical configuration of the medical device detector of murmurs.

A brainstorming on possible configurations for the device was carried out resulting in the implementation of a central control unit connected by cables to at least three transducers that would turn the sound signal into an electrical signal. The electric transducers would be placed in the following sites of the patient chest where auscultation is commonly performed: aortic area, secondary aortic area, lung area, tricuspid area and the mitral area, choosing to place 3, 2 or 1 at the same time, depending on the technique and the type of murmur that needs to be identified.

Figure 1 shows the CAD design of the device, in the exterior form chosen. Note the transducers and the main control unit.

Figure 1 CAD Design of the heart murmur detector

Development of the murmur classification algorithm

Figure 2 shows graphically the typical appearance of a Phonocardiogram. In this graphic, the Y axis shows the sound amplitude while the X axis shows time. Notice how at the beginning of each stage a high amplitude sound is located. These signals correspond to the characteristic sounds of the heart, which are easily audible with a stethoscope and happen to a more or less constant rate. The normal cardiac activity has 2 main sounds, called S1 and S2.

The first sound S1 is associated with the closure of the mitral and tricuspid valves. Both valves close almost simultaneously [1].
The second sound S2 is associated with the closure of the aortic and pulmonary valves. The aortic component precedes the lung, but generally cannot distinguish the closure of one over the other [1].
The location of each sound regarding the stages of the cardiac cycle is as follows: S1 is the main sound preceding the systole, S2 is the main sound preceding the diastole.

The proposal of this work to resolve heart murmur detection is to perform an identification of S1 and S2 by amplitude and time based on the information of the phonocardiogram, and also information about the time of the carotid pulse. The information of the phonocardiogram aids to locate S1 and S2 in the

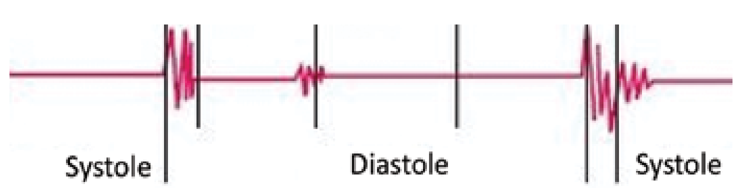

Figure 2. Section of a phonocardiogram showing the location of the systole and diastole. [1]

specific times, then not only the information of the phonocardiogram is used, but also the information of the times when the physician sees the carotid pulse in the patient, while recording the sound of cardiac activity in the phonocardiogram. Thus, the device will have two pieces of information for the analysis of S1 and S2. With the information corresponding to the temporal location of the carotid pulse, it will be possible to differentiate S1 of S2, because it is S1 that happens instants before the pulse is felt, so that the algorithm will temporarily associate S1 with the pulse.

It is important to note that different pathologies generate murmurs at different stages of the cardiac cycle. Then, if it is determined that the murmur is perceived during systole or diastole, this will add a differentiating factor between different pathologies. Table 3 shows a summary of the different pathologies that have been exemplified in this work and the corresponding location of the sound added in the cardiac cycle.

This information represents another feature to incorporate to the murmur detection algorithm according to the following statements:

A. *A sound recording with an added systole possibly corresponds to a heart with aortic / pulmonary stenosis or mitral or tricuspid regurgitation.*

B. *A sound recording with added diastole may correspond to a heart with aortic regurgitation or mitral or tricuspid stenosis.*

C. A sound recording with both a systole and diastole possibly corresponds to a heart with pulmonary regurgitation.

Table 3. Location of murmurs in cardiac cycle according to valvular disease. Source: Created based on information in [8].

Valvular pathology	Location of the murmur in the cardiac cycle
Aortic stenosis	Systole
Aortic regurgitation	Diastole
Pulmonary stenosis	Systole
Pulmonary regurgitation	Systole/ Diastole
Tricuspid stenosis	Diastole
Tricuspid regurgitation	Systole
Mitral stenosis	Diastole
Mitral regurgitation	Systole

In order to perform a limited test of the algorithm of identification with analysis of amplitude - time; a part of it is selected to be simulated by a computer. The selected section helped identify three types of phonocardiograms: a normal heart, a heart with a murmur by tricuspid regurgitation and a heart with a murmur by pulmonary regurgitation.
Simulation, then, had a sample from a normal phonocardiogram, a sample from a heart with pulmonary regurgitation and a sample from a heart with tricuspid regurgitation.

All phonocardiograms were pre-recorded and pre-diagnosed according to sources of references [7,8]; all digitally in a .wav sound file format.

The sections of the algorithm related to the analysis of amplitude and time and the location of the auscultation and the carotid pulse were not tested, because that information was not available in samples collected.

The partial simulation of the algorithm was performed with the use of LabView™. And the support of a programmer who was provided with all requirements that the program should meet, including the comparison algorithm of amplitude - time.

Figure 3 shows the interface to the user of the application of the developed simulation program for the murmur detection device. The LabView software was chosen as the right tool capable to partially implement the murmur detection algorithm for three out of the eight most common cardiac valve conditions. It has all the required capabilities to implement the rest of the algorithm and completely simulate the performance of the device. The user interface was well received by the physicians since it provided all the necessary information for a proper understanding and diagnosis of the phonocardiogram, such as the amount of cycles per minute, the systole and diastole segments and a heart animation that helps identify the phase of the cycle that is being analyzed.

Once the simulation concludes with the analysis of the Phonocardiogram, an output report is generated, an example as shown in Figure 4. The main output of the result is the diagnosis suggested by the simulator.

Through the evaluation it was possible to successfully test a section of the algorithm for the murmur detection, and the effectiveness of the following elements was demonstrated. Firstly, in a normal heart, S1 and S2 exceed an amplitude value that is not exceeded during systole and diastole: The value defined in the simulation was 0.3 - 0.4 of amplitude. The simulator was able to detect each S1 and S2 section of the phonocardiogram successfully. Secondly, S1 will have an interval length from 0.07 to 0.09 s and S2 will have an interval length from 0.08 to 0.1 s. In the simulation the chosen value was 0.08 seconds for both elements.

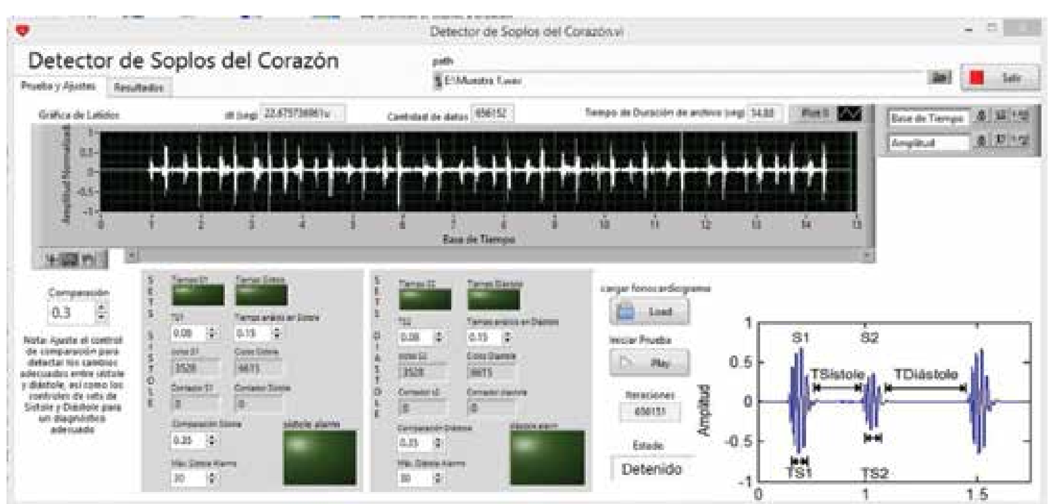

Figure 3. User interface for simulator of the murmur detector.

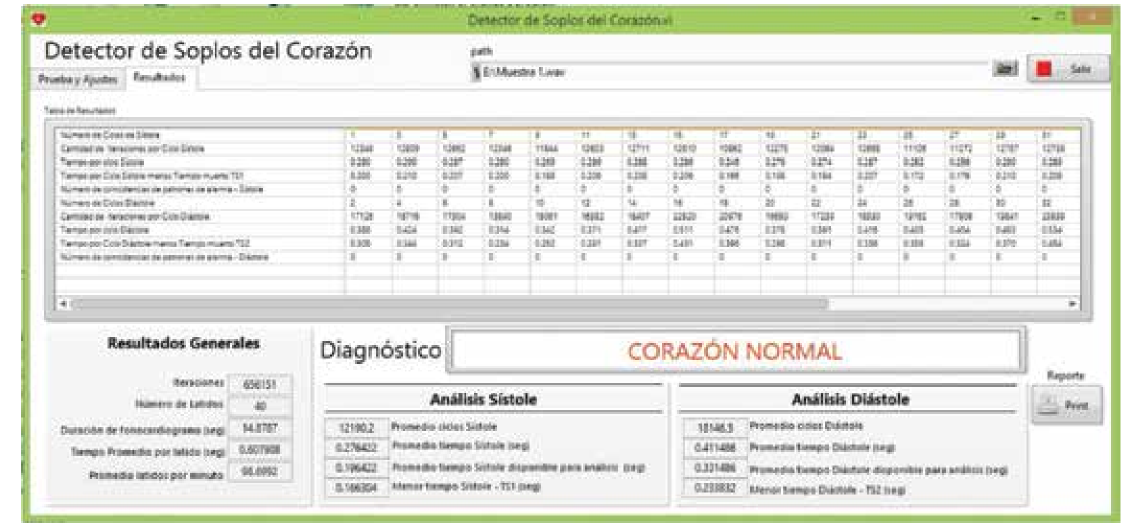

Figure 4. Results section of analysis from simulator of murmur detector.

Table 4. Summary of possible diagnoses scheduled in simulator.

Alarms	Diagnosis
No alarms	Normal heart
Alarms in systole	Tricuspid regurgitation
Alarms in systole	Pulmonary regurgitation

Table 5. Results obtained for number of hits, percentage of success and 95% confidence in the tests with the physicians. Statistical Kappa values are also shown.

Physician	Number of samples	Number of hits	Percentage of hits	95% CI	Statistical Kappas
1	9	7	77.78%	(39.99, 97.19)	0.66667
2	9	8	88.89%	(51.75, 99.72)	0.84071
3	9	5	55.56%	(21.20, 86.30)	0.36842
4	9	7	77.78%	(39.99, 97.19)	0.69492
5	9	9	100%	(71.69, 100.00)	1
6	9	8	88.89%	51.75, 99.72)	0.84071
7	9	7	77.78%	(39.99, 97.19)	0.68966
8	9	3	33.33	(7.49, 70.07)	0.11475

The simulator was able to correctly delimit S1 and S2, and not to confuse them with the components of systole and diastole, even if these were normal or with noise added. Thirdly, the time of systole is the shortest duration in the phonocardiogram of the S1 and systole set. During the test, it was found that the recommended values by the simulator for the time of analysis of the systole was 0.166 s in a normal heart, 0.622 s in a heart with pulmonary regurgitation and 0.267 in a heart with tricuspid regurgitation. In all cases, the values entered in the simulator were lower than these times. Fourthly, the time of diastole is the shortest duration in the phonocardiogram of the S2 and diastole set. The simulator recommended for the analysis time of diastole 0.234 s in a normal heart, 0.221 s in a heart with pulmonary regurgitation and 0.504 in a heart with tricuspid regurgitation. In all cases, the values entered in the simulator were lower than these times. Finally, all phonocardiograms that show amplitudes above a value of comparison in systole and in diastole were classified as a murmur. In all cases, the simulation achieved to detect the noises added to the systole and diastole, being able to detect the presence of a cardiac murmur. The comparison value chosen for the systole and diastole was 0.35 of amplitude.

Once the simulator finishes analyzing the entire file of the phonogram, it uses the information of the recorded alarms to suggest a diagnosis. In this test, there have been three possible results, according to Table 4.

As noted, in each case, the diagnosis was correct. The simulator was able to perform the correct evaluation for the sample phonocardiograms selected. It was possible to verify that in each case, the simulator correctly detected sounds S1 and S2, extracting them from the rest of the cardiac cycle. Since most of public medical centers in Costa Rica are of primary assistance, usually general practitioners carry out diagnoses. Therefore, quick, low cost and easy-to-implement options are desired to aid the physician to deliver an accurate diagnosis.

The chosen statistical analysis was agreement by attributes. Table 5 shows the results obtained for the number of hits, the percentage of hits and the 95% confidence intervals for each of the participating physicians.

The results show that the level of success among the participating physicians is quite variable. The values obtained were from a 33% to a 100% success rate. These results, on average, give a level of success of 75%, which is an acceptable result. Because of the limited sample size, the ranges of the confidence intervals at 95% are quite large.

In addition, the Kappa statistic was calculated for each of the medical evaluators, in order to measure their success rate with respect to the true diagnosis of the samples used in the study. The results are also shown in Table 5. However, this exploratory study showed that agreement by attributes in this case was not acceptable. More studies with a larger sample size are required to support that this tool is a viable solution in primary care centers in Costa Rica, despite the good reviews from the participating physicians.

The calculation of the rates of sensitivity and specificity give a measurement of the effectiveness of the diagnosis made during the simulator's evaluation of the heart murmur detector device. The values for sensitivity and specificity calculated according to equations (1) and (2), respectively were 91.7% and 82.6%.

It is clear that for the physicians it is easy to identify that there is an abnormality in the blood flow, demonstrated by the good sensitivity result. However, in some cases it was difficult to classify each of the pathologies correctly, which shows that the device needs further improvement to include correct identification all the known conditions.

Based on the research, preparation of proposals and the analysis of the first results it was concluded that the implementation of an automatic device for detection and diagnosis of pathologies of the heart valves using phonocardiograms is possible, and the technology and knowledge needed are currently available to achieve this objective.

However, the objective of a device of murmurs detection is not to replace the skills of the medical staff in primary care center, but rather, to be of support for their daily work. A proper diagnosis of a cardiac pathology should not be limited to only one piece of information such as the automatic analysis of a phonocardiogram, but rather requires as many pieces of information about the patient, such as physical examination, medical history, auscultation examination, information about the symptoms the patient provides, among others. All this will help to improve the accuracy of diagnosis and the chances of recovery of the person.

Conclusions

1. The heart murmurs detector is a device that was accepted by the physicians during the study and it represents an opportunity for improvement of the primary care centers in Costa Rica.

2. It is evident that for the physicians it is easy to identify that there is an abnormality in the sound of blood flow, shown by the good result of sensitivity of 91.7%.

3. LabView programming software has all necessary capabilities to implement the rest of the algorithm and completely simulate the functioning of the device for the murmur detection.

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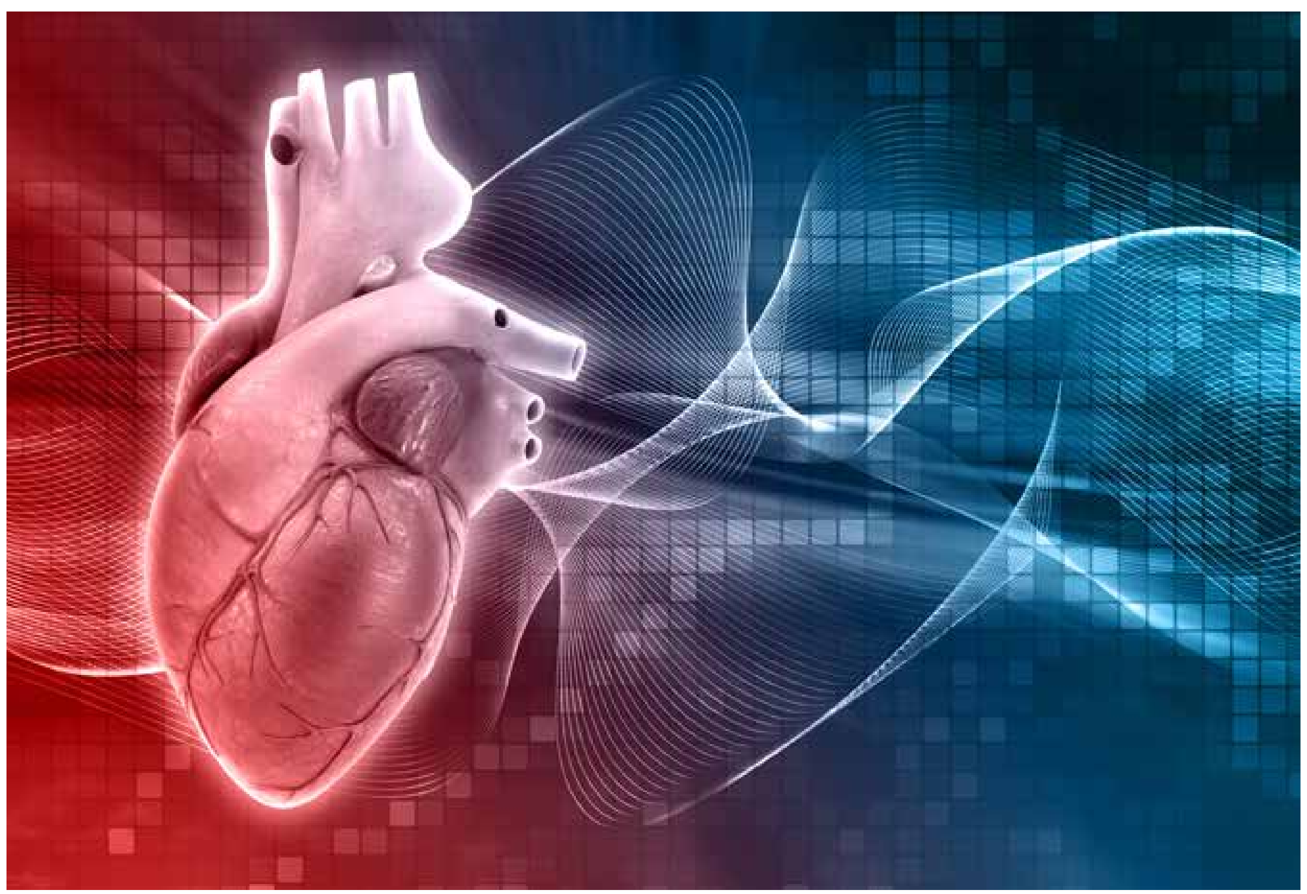

Promoting our program

Design of Medical Devices Conference

Participation in the 2017 Design of Medical Devices Conference, organized by the University of Minnesota, was a great success.

According to Ricardo Esquivel Isern, director of the Medical Devices Engineering Graduate Program at TEC, the participation with a stand in the conference exhibition fulfilled the main objective of strengthening ties and promoting our academic proposal.