Bayesian Networks and Influence Diagrams as Valid Decision Support Tools in Systolic Heart Failure Management

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Abstract

Heart failure is a complex syndrome that affects more than 5% of the population over 65, and whose direct costs account for a 2% of the health budget in developed countries. The existing interrelations among the different causes, mechanisms, symptoms and treatments associated to the condition complicate its modeling and, hence, the development of decision support tools which assist health professionals. This article describes the use of a Bayesian network in the modeling of heart contractility dysfunctions reflected in the condition of systolic heart failure and the use of influence diagrams in the decision for treatment actions. The resulting network estimates the probability of a patient for developing an asymptomatic ventricular systolic dysfunction and systolic heart failure from the specification of signs, symptoms, risk factors, cardiovascular disorders or diagnosis tests results. Based on that, the network informs about the convenience of applying a preventive or a corrective treatment.

1. Introduction

Despite some criticism against the use of probabilistic methods in expert systems, probability remains as one of the best methods for handling uncertainty.

The impossibility of applying the classic Bayesian method to most part of the real world problems and the introduction of new methods such as certainty factors or fuzzy logic, questioned the application of probability in the field of artificial intelligence. However, in the 80s, the development of Bayesian networks allowed the creation of a causal reasoning model with a solid theoretical basis which refused the objections against the use of probability. In this way, influence diagrams can be considered as an extension of Bayesian networks, where the use of decision and utility nodes allow the resolution of decision taking problems.

In the 90s, the number of researchers, universities and companies using Bayesian networks grew exponentially. In fact, nowadays there exists a great variety of Bayesian expert systems in diverse specialities. One of these specialities is medicine, where the use of uncertainty in the conceptual modelling of knowledge is very common.

Heart Failure (HF) is a principal complication of most heart diseases. The heart's inability to pump a sufficient amount of blood to meet the needs of the body tissues may be due to insufficient or defective cardiac filling (diastolic HF) and/or impaired contraction and emptying (systolic HF). Compensatory mechanisms increase blood volume and raise cardiac filling pressures, heart rate, and cardiac muscle mass to maintain the heart's pumping function and cause redistribution of blood flow. However, despite these compensatory mechanisms, the ability of the heart to contract and relax declines progressively and the HF worsens.

The most common cause of chronic HF is myocardial dysfunction, mainly due to ischemic heart disease. The clinical manifestations of HF vary enormously and depend on a variety of factors, including the age of the patient, the extent and rate at which cardiac performance becomes impaired, and the ventricle initially involved in the disease process. Its cardinal manifestations are dyspnoea and fatigue and fluid retention. Symptoms of exercise intolerance are typically assessed by the New York Heart Association functional classification [1].

In Spain, HF is the third leading cause for cardiovascular death. In 2000, 4% of men's and 8% of women's deaths were due to HF [2]. According to the statistics [3], HF incidence approaches 10 per 1,000 of the population after age 65, 75 percent of HF cases have antecedent hypertension and about 22 percent of male and 46 percent of female heart attack victims can be disabled with heart failure within 6 years. In the United States, hospital discharges for HF rose from 377,000 in 1979 to 995,000 in 2001, an increase of 164 percent.

In any health care system, hospital admissions represent a disproportionate component of total health care expenditure. Not surprisingly, considering the high rates of hospitalisation for HF and the ongoing treatment and care it requires, the overall management of HF requires a significant amount of health care expenditure in industrialised nations. For this reason, improvements in the syndrome management solutions are demanded. However, the existing interrelations among the different causes, mechanisms, symptoms and treatments associated to HF complicate its modelling and, hence, the development of convenient decision support tools. Moreover, due to their great number, many HF patients are treated by general practitioners for whom the use of specialized assisting tools may be helpful.

This article describes the use of a Bayesian network in the modelling of heart contractility dysfunctions reflected in the condition of systolic heart failure and the use of influence diagrams in the decision for treatment actions. The obtained results suggest that Bayesian networks and influence diagrams could be used a valid decision support tools in heart failure management.

2. Methods

The inherent complexity and the existing interrelations among the different causes, mechanisms and symptoms associated to the heart failure condition, make its modeling process lengthy and complicated, and require detailed analysis of all the involved factors.

The model presented in this article considers the main causes, symptoms, signs and treatments of systolic heart failure (SHF) and tries to reflect in the most appropriate way the different interrelations existing among them. In order to simplify the network design and avoid unnecessary complexities, some simplifications have been considered. Nevertheless, they have tried to maintain the truthfulness of the representation.

2.1. Network structure

The referred network considers the existence of 8 different node types:

1. 'Cause nodes': they identify the main causes or factors that can influence the development of symptomatic SHF or asymptomatic systolic ventricular dysfunction or AVD (e.g. age, smoking, hyper-cholesterolemia, hypertension, myocardial infarction, atrial fibrillation, ischemic cardiopathy, dilated cardiomyopathy and valvular disease).
2. 'Syndrome nodes': they represent the different HF modalities considered by the network (i.e. SHF, AVD and compensated HF).
3. 'Symptom nodes': they identify the most significant symptoms derived from the development of the SHF condition (i.e. fatigue, dyspnoea and peripheral edema).
4. 'Sign nodes': they represent the main anomalies that can be observed by a physician during the anamnesis process (i.e. R3 gallop, lung murmur, hepatic congestion and neck congestion).
5. 'Result nodes': they represent the main diagnosis tests results that suggest the development of SHF (i.e. cardiomegaly, low LVEF and normal LVEF).
6. 'Functional Capacity nodes': they allow the model to consider the patient's functional capacity. In this way, a first node identifies the activity beard by the patient according to the NYHA criteria and a second one establishes the SHF level derived from this capacity.
7. 'Decision nodes': they represent the possibility of applying a treatment that influences the progression of the symptomatic or asymptomatic condition. Because of this reason, two types of treatment have been considered: preventive treatment and symptomatic treatment.
8. 'Utility nodes': they express the cost and benefit derived from a preventive or symptomatic treatment decision, or the arrival to a specific node state representing the syndrome evolution.

2.2. Relations among network nodes

The causal relations established among the SHF network nodes are depicted in Figure 1.

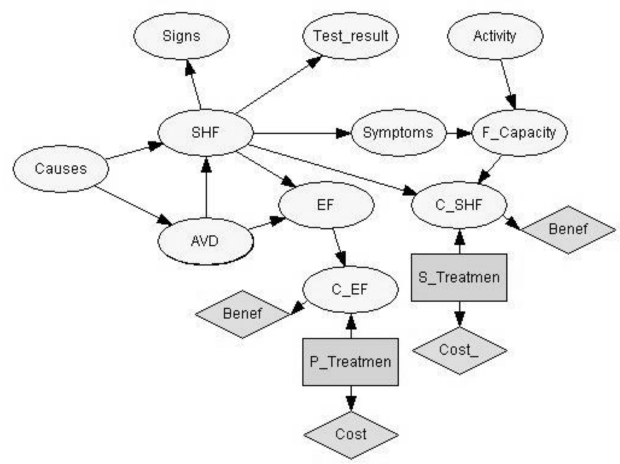

Figure 1 – Causal relations observed by the SHF model.

The main criterion followed in the network design has been the representation of the 'etiology' → 'syndrome' → 'symptoms' relation. Then, the nodes needed for the representation of the patient's functional capacity and the possible syndrome evolution according to a treatment decision have been added.

The network establishes smoking and hyper-cholesterolemia as factors that can influence the development of any kind of cardiovascular pathology. These pathologies, together with other two risk factors such as hypertension and age, have been defined as the main causes of symptomatic SHF. On the other hand, and concerning asymptomatic ventricular dysfunction (AVD), one main cause has been defined. Acute myocardial infarction remains as the subjacent reason for more than a half of the AVD cases.

Apart from the 'Cause nodes', the rest of the network elements start from the SHF and AVD nodes. That is the case for the elements referred to the possible symptoms, signs and diagnosis tests results, which can be observed in a HF patient. Moreover, as shown in Figure 1, the network also represents the influence that both symptomatic and asymptomatic SHF may have on LVEF.

Concerning the decision process modeling, both the SHF and the AVD treatments follow the schema proposed in Figure 2. This schema reflects the fact that the application of a treatment has an associated cost. However, this cost is compensated by the benefit derived from the improvement in the patient's evolution.

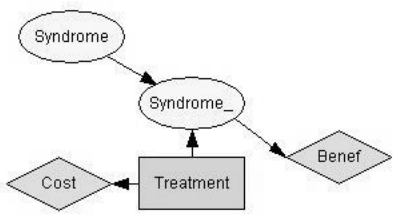

Figure 2 – Decision model for treatment application.

The creation of two decision processes has forced the definition of an adoption or precedence order, which is established by the purpose of each kind of treatment. In this way, the first decision to be considered is the application or not of a preventive treatment. Only in the case that the syndrome evolution derives in symptoms appearance, the symptomatic treatment is considered. This decision scheme corresponds with reality where the symptomatic treatment includes the preventive one.

Finally, the 'Functional Capacity nodes' represent the level of HF presented by a symptomatic patient and take part in the decision on the application of a symptomatic treatment.

2.3. States and probability tables

Each node of a Bayesian network is typified by the set of possible states of the random variable it represents, and by a table that express the probability of each one of them in function of the states of the causal nodes.

The probability tables used for the establishment of the SHF network have been estimated from heart failure hospitalization data of non-selected patients in the HGU Gregorio Marañón in Madrid, Spain [4].

2.4. Utility functions

Starting from the influence in the probability of reaching a desired state, utility functions allow estimating the convenience of a decision.

In the SHF network, these functions estimate the utility of applying a pharmacological treatment to SHF or AVD patients. In both cases, the calculation considers two factors: the cost derived from the drugs acquisition and the benefit obtained from the improvement in the syndrome progression.

For this purpose, the network makes use of two utility nodes, one considering cost and the other considering benefit, that are associated to the decision node and the node representative of the syndrome evolution respectively. The associated utilities for these nodes are negative or zero in the case of cost and positive or zero in the case of benefit. In this way, and according to the network state, the weighed up balance among both indicators allows determining the utility of a decision.

The network considers that the costs of the treatments for the different HF levels get dearer as the level increases. This is consistent with the fact that the higher level treatments include the lower ones. Finally, and concerning the utilities associated to the different states that indicate the syndrome evolution, positive values weigh the desired states up while negative values promote the opposing effect. The difficulty to find concrete values for those utilities has made that these are a result of a reiterative adjustment process of the network.

3. Results

Starting from the design criteria described in the previous section, the SHF network was implemented and compiled by making use of a specialized software tool for the development of Bayesian networks [5]. After that, a set of tests were realized in order to check the network correctness mainly in two aspects: first, to assure the coherence among nodes states as new information is introduced in the network and the initial state uncertainty is reduced and, second, to prove the suitability of the suggestions provided by the network concerning therapeutic decisions.

The first tests were focused on the validation of the 'Symptom nodes', the 'Sign nodes' and the 'Cause nodes'. The 'Symptom nodes' provide information about the probability of occurrence of the dyspnoea, fatigue and oedema states in a patient. These are very common SHF symptoms; however their presence does not imply HF development. In this way, though in the initial state the network reflects a high probability for the presence of these symptoms, this is not related to the probability of HF development. In the cases where the network was enriched with data informing about the occurrence certainty of these symptoms, the probability of HF development was increased but still remained non-significant. It was proved that only in those cases where the certainty of existence of any sign detected during the anamnesis or a positive diagnosis result (e.g.

cardiomegaly) was included, the probability of HF development was over 0.5.

On the other hand, in those tests where the certainty of SHF was introduced, the probability of appearance of cardiac or lung murmurs was over 0.5 as well as in the case of dyspnoea, oedema and fatigue symptoms. Exceptions to this behaviour were neck and hepatic congestion signs.

Concerning risk factors, age (i.e. over 74) was the most influential factor, which is consistent with reality. Combined with atrial fibrillation, the probability of developing SHF was about 0.52. Moreover, the combination of two risk factors, such as age and hypertension, with any of the cardiovascular pathologies considered by the network accounted for probabilities of developing SHF over 0.5. In case of not existing any of these pathologies, the probability was reduced until 0.2.

In a similar way to practice, the probability of having a low ejection fraction (EF) was directly related to the presence of SHF or AVD. The existence of a low EF in the absence of symptoms was consistent with the existence of AVD, while symptoms appearance slightly raised p (SHF) over 0.5.

Finally, the rest of the realized tests were focused on the correctness of the treatment suggestions. In this way, the network starts to recommend the application of a preventive treatment at the same time that the probability of having a low ejection fraction is over 0.5, independently of the dysfunction being or not symptomatic. In those cases where the probability of developing a symptomatic SHF is over 0.5, the network starts to advise the application of a symptomatic treatment. This treatment depends on the functional capacity reported by the patient and it is assessed as a function of the level of activity beard by the patient. By default, the network considers that the patient is able to reach a light level of activity, so this make that the treatment configuration for patients with class 3 SHF is advised by default. Because of this reason, for the provision of a correct advice the network needs to be provided with a certainty about the patient's functional capacity.

Due to the relation existing among the SHF and the AVD with the EF, once the network detects a symptomatic dysfunction, both the preventive and symptomatic treatments are advised. Considering the fact that the preventive treatment is included into the symptomatic one, only the second one is considered.

4. Discussion and conclusions

Bayesian networks reveal as an appropriate tool for the representation of knowledge in the heart failure domain and for the subsequent development of decision support tools. In this way, the network described in this article allows a generic though quite approximate modelling of the heart systolic dysfunction. This result is based on the detailed study of the procedures involved in HF management and in the careful choice of the most representative network concepts in terms of causes, symptoms, signs and risk factors.

The proposed design considers the main risks and unchaining factors that derive in the development of SHF and AVD. Though the realisation of diagnosis tests is not directly referenced, this relation is established at a sign and test results level. The network informs about the convenience of applying a preventive or a corrective treatment. In the latter case, after the introduction of the patient's functional capacity, different drug combinations based on the literature [6, 7] are suggested.

The use of influence diagrams allows the creation of a decision process based on the adequate assessment of cost and utility functions. These functions consider the cost of the treatment and the benefit obtained by the patient with its application.

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