Time Dependent Fuzzy Cognitive Maps for Medical Diagnosis

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Abstract. Time dependence in medical diagnosis is important since, frequently, symptoms evolve over time, thus, changing with the progression of an illness. Taking into consideration that medical information may be vague, missing and/or conflicting during the diagnostic procedure, a new type of Fuzzy Cognitive Maps (FCMs), the soft computing technique that can handle uncertainty to infer a result, have been developed for Medical Diagnosis. Here, a method to enhance the FCM behaviour is proposed introducing time units that can follow disease progression. An example from the pulmonary field is described.

Keywords: Fuzzy Cognitive Map, time evolution, medical diagnosis.

1 Introduction

In medicine, the capability of immediate diagnosis and treatment is always a necessity and under constant investigation. Doctors have to make immediate decisions and determine the appropriate treatment. Pulmonary diseases include a set of different and complementary cases/diagnosis that cannot be easily discerned due to their similar characteristics. Differentiating diseases that have common or similar symptoms and/or missing information based on the first symptoms may lead to a wrong decision. Thus, differential diagnosis is a highly complex procedure that demands the incorporation of many factors, with missing or conflicting information and taking into consideration various aspects from seemingly unrelated factors. To overcome ambiguity, omissions and imprecision which can infer misleading results, computational intelligence methods has been proposed to solve many complex problems by developing intelligent system. Fuzzy logic has proved to be a powerful tool for decision-making systems [1].

Medical Decision Support Systems (MDSS) are planned to support human decision making successfully by evaluating information from different sources, combining it to support clinicians' decisions concerning diagnosis, therapy planning and monitoring

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of the disease and treatment processes. Medical Decision Systems have to consider a high amount of data and information from interdisciplinary sources (patient's records and information, doctors' physical examination and evaluation, laboratory tests, etc.) and, in addition, information may be vague, missing or not available. Thus, MDSS are complex systems involving inexact, uncertain, imprecise and ambiguous information [2]. These systems can provide assistance in crucial clinical judgments, particularly for inexperienced medical professionals.

The method of differential diagnosis that is presented in this work is based on Fuzzy Cognitive Maps (FCMs). Here a new type of FCMs is introduced where the values of concepts and the values of weights are changed according to the time interval. This is in accordance to the real world problems where the influence from one concept to another is not instant and it differs from one interconnection to another one, so here time influence is considered and introduced. A FCM tool is developed and used for medical differential diagnosis of two pulmonary diseases: acute bronchitis and common-acquired pneumonia.

The main contribution of this paper is the introduction of the temporal aspect, which is essential for cases where time is significant because time evolution highly influence the final result. Such a field is medical applications and here the proposed approach is successfully applied for differential diagnosis of pulmonary diseases. In the following sections, the FCM-Medical Decision Support Tool (FCM-MDST) is introduced and described including the time dependent features because the progression of diseases are influenced by the time and so SCM-MDST is able to lead to a decision per time unit. Specifically, section 2 refers to the principles of FCM, section 3 describes the need for using MDSS, section 4 describes the proposed tool and how it was developed, while in section 5 results and comments are stated.

2 Fuzzy Cognitive Map

Fuzzy Cognitive Map belongs to the soft computing approaches and it originated from the combination of Fuzzy Logic and Neural Networks. It is a modelling method for complex decision systems. An FCM is illustrated as a causal graphical representation, consisting of interrelated concepts. It was introduced by Kosko [3] as an extension to Cognitive Maps [4]. The general graphical illustration of FCM is a signed, weighted graph with feedback. Nodes of the graph are concepts, which correspond to variables, states, factors and other characteristics that are used in the model and describe the behaviour of the system [5]. FCM nodes constitute the set of concepts $C = \{C_1, C_2, \ldots, C_n\}$. Arcs (C_j, C_i) represent the causal link between concepts (how concept C_j causes concept C_i). The weights of arcs form the weighted values of the matrix (w_{nxn}). Each element of the weight matrix w_{ji} belongs to $[-1,1]$.

The value A_i of the concept C_i expresses the degree of its corresponding physical value. At each simulation step, the value A_i of a concept C_i is calculated by computing the influence of other concepts C_j's on the specific concept C_i following the calculation rule:

$$A_i^{k+1} = f(A_i^k + \sum_{\substack{j \neq i \\ j=1}}^{n} A_j^k w_{ji}) \quad (1)$$

where A_i^{k+1} is the value of concept C_i at simulation step k+1, A_j^k the value of the interconnected concept C_j at simulation step k, w_{ji} is the weight of the interconnection between concept C_j and C_i, and f is a sigmoid threshold function:

$$f = \frac{1}{1+e^{-\lambda x}} \quad (2)$$

where $\lambda>0$ is a parameter that determines its steepness

The graph that illustrates the FCM consists of nodes and weighted interconnections. Signed and weighted arcs connect various nodes. This connection represents the causal relationships among the concepts. Fig. 1 illustrates a simple FCM with different aspects in the behaviour of the system, showing its dynamics and allowing the systematic causal propagation [6].

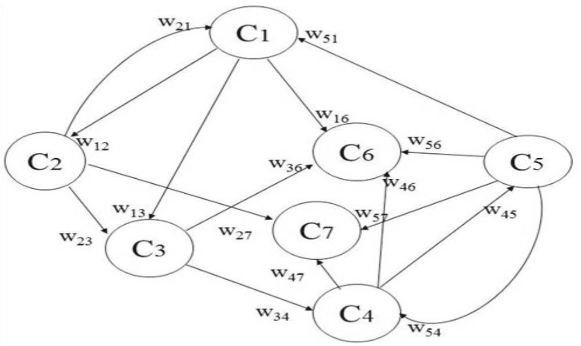

Fig. 1. The fuzzy cognitive map model

The sign of the weight show the causal relationship between concepts. That is, if $w_{ji}>0$ then concept C_j increases C_i, if the weight is $w_{ji}<0$ then concept C_j decreases C_i, while if $w_{ji}=0$ concept C_j has no causal effect on C_i. Moreover, the values of the weight indicate the strength of the influence between the concepts. The direction of causality (forward and backward) shows which concept causes another concept. For optimizing the behaviour of the system, various learning methods have been developed [7], enhancing the basic FCM and succeeding in better results.

3 FCMs for Medical Decision Support Systems

Medical Decision Support Systems follow the general nature of medical interventions: predict (predictive machine), prevent (preventive medicine), heal (curative medicine), or at least comfort (medical assistance) [8]. For this goal, a patient's particular situation must be considered and supplemented with an appropriate examination to give a more certain result. Complexity of MDSS is increased as they are consisted of irrelevant and relevant subsystems and elements, taking into consideration many factors that may be complementary, contradictory, and competitive;

these factors influence each other and determine the overall diagnosis with a different degree. A MDSS usually extracts causal knowledge from the appropriate medical domain; it builds a causal knowledge base and makes inference with it. Fuzzy Cognitive Map is a model that can give this opportunity.

When medical experts have to make a decision, they should take into consideration a variety of factors (concepts) giving to them a particular degree of importance (weight) on how much influence the other concepts. They have a conceptual model in their mind with interconnected factors until finally reach to a decision. FCMs are highly applicable in medicine. They are used for medical decision making, reasoning, differential diagnosis, prediction and/or treatment purposes. In general, medical decision is a complex procedure as many factors and functions should be taken under consideration before the final decision. However, the interest of using MDSS is not only on the accuracy and prediction of the results but also into the transparency and interpretability from the professional that use the MDSS during his daily work.

FCMs can model any real world system as a collection of concepts and causal relation between concepts. Fuzzy Cognitive Maps have been successfully used to develop Decision Support Systems (FCM-DSS) for various cases such as diagnosis, prediction, treatment etc. Georgopoulos et al. used successfully the FCM-DSS for differential diagnosis [9]. FCM-DSS has been also used in radiotherapy for determining the success of the radiation therapy process by estimating the final dose that delivered to the target tumor [10]. As a diagnostic support system, FCM-DSS has been used for labor modelling giving promising results [11]. FCM proved to be a simple and transparent way for representing and useful to describe any system in many fields such as engineering, medicine, and business and so on.

4 FCM System for Pulmonary Differential Diagnosis

Acute bronchitis and common-acquired pneumonia [12] are two pulmonary disorders that have many factors (symptoms) in common. FCM construction for these two pulmonary diseases demands four stages: the definition of the factor-concepts (symptoms) and decision concepts, definition of time unit that important changes can be noticed, the determination of weights and the definition of weight change according to time unit and additional parameters.

- Concepts: Factor concepts (symptoms) can be derived both from literature and experts in order all possible cases to be taken under consideration from the system. Thus, concepts can be collected from literature taking every possible and rare circumstance into account that experts do not usually find during their daily incidents. Experts can also add other concepts from their experience and knowledge. In this way, every possible concept, even the rarest, contribute to the final result.
- Time unit definition: Experts have to define the time unit (interval) which is the time that experts regard as adequate and capable to change the weights in a remarkable degree. This time can be ranged according to the under investigation differential diagnosis and speciality.

- Weight determination: Experts will set the weights during the whole progression of a disease, taking into consideration their theoretical background and their experience knowledge. They define the degree of interconnections linguistically and through a defuzzification process a numerical value is given.
- Weight per time unit determination: Pulmonary diseases may need one day to few days in order a patient to present the most symptoms. For this reason, experts have to determine the new weights taking into consideration not only the initial interconnections among the concepts but also how the degree of this relationship is changing as the time goes by. This weight evolution depends on additional factors, which finally determine the direction of change.
- Simulation: The cycle of simulation for each time interval stops when there is achieved a sufficient difference between two decisions. The suggested difference is defined by experts and it is dependent on each case and application area.

Regarding to the weight definition, experts will set the weights during the whole progression of a disease, taking into consideration their theoretical background and their experience knowledge. Experts determine the interconnections using fuzzy rules; a linguistic variable that describes the relationship between the two concepts is inferred according to each expert who also determines the grade of causality between the two concepts. That is, after the definition of concepts, experts are asked to propose the degree of influence among all the concepts, using IF- THEN rules. These rules are according to the statement:

For time unit 0…N: " IF a { none, very-very low, very low, low, negatively medium, positively medium, high, very high, and very very high} change in concept value C_i occurs THEN a { none, very-very low, very low, low, negatively medium, positively medium, high, very high, and very very high} change in value Cj is caused THUS the influence of C_i to C_j is a T_{Cij}{influence}". In this way each influence is determined. The inferred fuzzy weights across experts are aggregated and deffuzified giving an initial numerical weight in the interval [-1, 1]. Thus, basic weights and weight matrix are defined.

In addition to the initial weights, experts have to determine which concepts' dependencies (weights) have lower or bigger influence during the progression of the disease. The direction of this change depends on contribution of some other parameters, such as the age, if the patient smokes (how many years and the amount of cigarettes) or not and if there is another co-morbidity. That is, as the days pass the interdependences among some symptoms have different evolution in time compared to others and this change depends on both time and the additional parameters; interconnections can become weaker or stronger. Taking these changes into account during the simulation process, experts need to define the change for each time unit. Thus, for each interconnection influenced by the time, new values on each additional parameter will lead to the appropriate weight change. Linguistic degrees are used to indicate the direction of change (such as none, very-very low, very low, low, negatively medium, positively medium, high, very high, and very very high). These degrees correspond to negative or positive direction. In this case the statement will be:

For time unit 0 ....N: "IF (Additional Factor 1=TRUE (AND/OR Additional Factor 2...3 =TRUE) AND IF a { none, very-very low, very low, low, negatively medium, positively medium, high, very high, and very very high} change in concept value C_i occurs THEN a { none, very-very low, very low, low, negatively medium, positively medium, high, very high, and very very high} change in value C_j is caused THUS the influence of C_i to C_j is a T'_{Cij} {influence} ELSE {keep the time unit 0 influence value (T_{Cij}{influence}).The inferred new fuzzy weights, for each time unit and for each parameter, aggregated and defuzzified giving new numerical weight($w_{ij}{}' = w_{ij}/t$) in the interval [-1,1] to the correspondent interconnections. This procedure can approximate better real life situations, as the weights can change per time unit incorporating more elements and parameters that characterize each one patient.

Experts should also set the correspondent weights, following the way that each disease is evolving. Apart from that, disease progression includes activation and/or deactivation of specific concepts and as a result, activation and/or deactivation of their correspondent weight-values (interconnections).Thus, each patient case is a different case and the progression of symptoms depends on time and additional factors. For example, the symptoms for the same disease for two different patients follow different evolution and some of them may obtain less or bigger meaning in case of patient's smoking or not. It is generally a multiple-aspect process. The use of weights per time unit and per relative additional factor tries to make the FCM able to more accurately represent a wide variety of patient profiles.

Figure 2 illustrates the FCM model for the differential diagnosis of the two pulmonary diseases: acute bronchitis and common-acquired pneumonia. It should be underlined that some interconnections are omitted as the high complexity makes it unreadable.

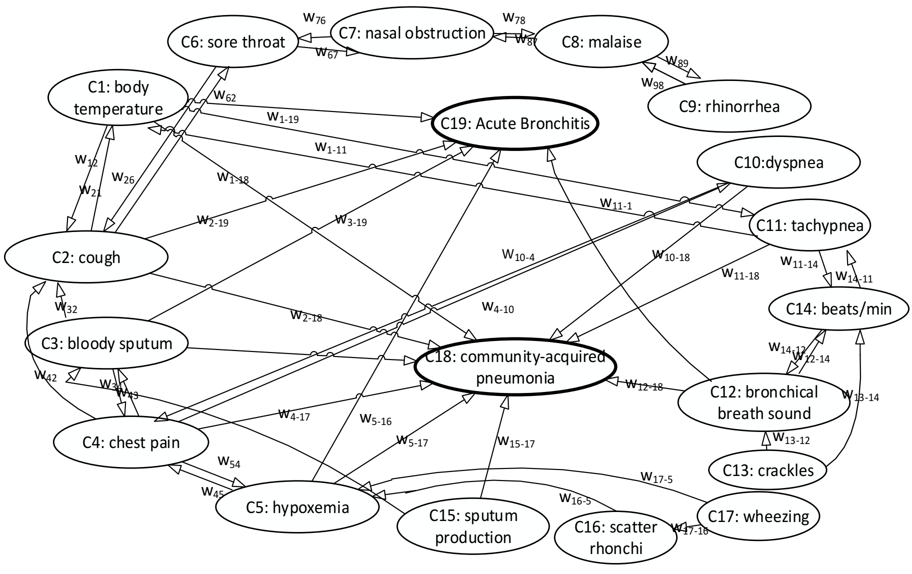

Fig. 2. FCM for pulmonary differential diagnosis

Figure 2 illustrates the factor-concepts (concepts C1 till C17) and the two decision concepts for differential diseases (concepts C18 and C19) which are in bold circles. The direction of the illustrated arrows shows the direction of dependence and the weights are the weights according to experts for each time unit. The FCM model is characterized by high complexity and many factors should be combined both from the patient's history and the clinical examination in order to have the final result.

4.1 FCM-Medical Decision Support Tool Description

Acute Bronchitis and Community-acquired pneumonia are two severe lung diseases that have some common concepts-factors, especially in their non-typical or first appearance. The following example is based on the previous described methodology. Table 1 contains the factor concepts which are symptoms that can be retrieved from patient's answers and other that demand doctor's examination (such as bronchical breath sound, crackles, rhonchi, wheezing, hypoxemia and so on) and the diagnosis concepts. The severity of each factor-concept, the appearance time and the duration of each symptom may differ from day to day, rendering the insertion of a time interval necessary, such time can be one day for those disorders. As progression of pulmonary disorders depend on time, it is possible concepts that are not presented as first symptoms of a disease will be initially deactivated (equal to zero), while the deactivated ones can become activated in the following days. Thus, the correspondent interconnections may be zero or have a different value for a time unit, while they can be changed or activated for another. Time unit will be the time interval that experts will have judged as critical and capable to provoke a change to the factor/concepts and, as a consequence, to the weights of interconnections. In the described case, we will regard this time unit to be one day, as hour-intervals do not make a big difference for these two diseases. The physician has to insert in addition to the initial values of concepts and the time (day) that they firstly examine the patient.

The factor-concepts (symptoms) are divided into two categories: factor-concepts that are set by the doctor according to the patient's answers and from his/her history records and those which are activated according to clinical examination's results such as auscultation, measurement of oxygen and so on. In this way, the system is trying to handle the human uncertainty, the omission of information derived from patients and enhance the result adding the clinical findings into the final judgment. Table 1 contains concepts' separation as: factor concepts which are related to patients' judgment and history and those that need clinical examination from a doctor and the diagnosis concepts.

The initialization of the factor concepts according to patients are based on the answers they give during the doctor's questions. These answers are highly subjective and depend on many other factors that characterize the patient as individual, that is, many symptoms may have been overestimated by the patient (because of his/her fear) or underestimated. The other factor-concepts, which are according to clinical examination, are subjected to the capability and judgment of the specialized doctor to characterize and criticize the severity of findings, while other concepts are more objective, such as tachycardia, hypoxemia, tachycardia and fever, as they are based on

Table 1. Concepts‘ separation

Factor Concepts According to patient's answers	According to doctor's clinical exam	**Diagnosis Concepts**
C1: body temperature		
C2: cough	C5: hypoxemia	
C3: bloody sputum	C12: bronchical breath sound	
C4: chest pain		
C6: sore throat	C13: crackles	C18:Acute Bronchitis
C7: nasal obstruction	C14: beats/min	C19:Community-acquired pneumonia
C8: malaise	C11: tachypnea	
C9: rhinorrhea	C16: scatter rhonchi	
C10: dyspnea	C17: wheezing	
C15: sputum production	C1:body temperature	

medical equipments' results. The system is trying to give the appropriate values for each symptom, handling the uncertainty and multi-influenced symptoms.

The gradation of severity of each symptom, as it is illustrated to the user interface and can be used by the physician, is linguistic and represents the degrees that each concept can take. For example, fever gradation can be: hypothermia (<35.6^o), normal (35.7-37.3^o), slight fever (37.4-37.8^o), high fever (37.9-39.0^o), very high fever (39.1-40.9^o), hyperpyrexia (>41^o). Cough degrees can be: no cough, productive cough, non-productive cough. Similarly, the rest symptoms are defined according to their possible degrees.

Doctor has to insert the time (day) of starting the simulation. In relation to this day the weights of some concepts have less or more interference to the final result, in proportion to the existing additional factors. Thus, the system can use the appropriate weights according to each case. The use of the correspondent to the time weights, make the system able to take these changes into account. This adaptation enhances the system and allows it to reach more confident results. The system can run as many times as the number of time units specifies.

In fig.3 we can see an interface of the proposed tool which includes the factor concepts of the FCM model and the results for each time interval. The user interface allows the doctor to insert the values, define the patients' additional factors based on his/her history. The results are presented in another window. The results are presented per day and specify whether a clinical examination was performed or not, in order to be able to give the appropriate significance. Based on the results illustrated in the results window the doctor will infer his final diagnosis / decision.

The results will be an estimation of the possible final diagnosis, taking into consideration many factors during each time interval /day. The simulation results through the time interval/days may enhance the first diagnosis or lead to the opposite one as more specific patient's characteristics can be added and change the result. The doctor can judge the simulated results through the days and decide if they are accepted or not, forming his final decision.

When the doctor does not insert values at a time unit this means that there is no other concept triggering. Then, the system updates the weighted interconnection according to the experts' definition and there will be produced a new diagnosis based on the existing concept values. In the following time units, new concepts may be triggered while other may be deactivated. Thus, using the updated weights another decision is reached.

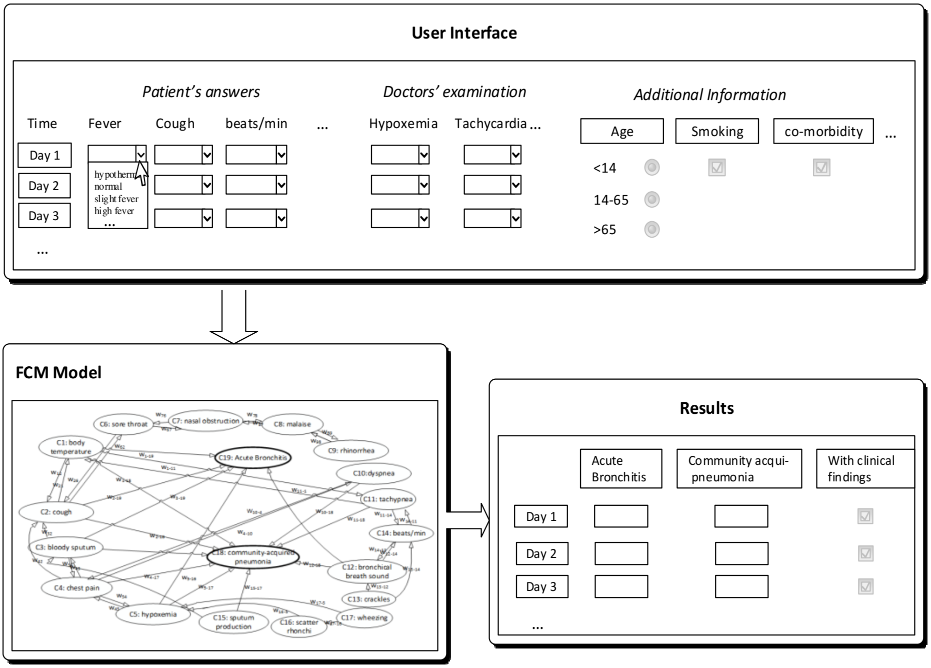

Fig. 3. Tool for differential diagnosis of acute bronchitis and community-acquired pneumonia

5 Conclusion - Comments

In this work, there was proposed a new Fuzzy Cognitive Map model that takes into consideration the time dependence among concept and a Medical Decision Support tool for pulmonary diseases was developed. This tool provides to the doctor a first estimation of the patient's situation. The user of the tool is the doctor who asks the patient to recall and refer the symptoms during the previous days and insert the values to the appropriate concepts. For each day the patient may present some of the symptoms (concept-factors), so the doctor can activate the correspondent concepts with values that ensue from the answers of the patient. The following days some of the symptoms may recede or not, which means change of their value, while others can be presented. Thus, the doctor can activate and deactivate other concepts and/or change their values. If the doctor examines the patient, s/he should insert the values to the system by activating the correspondent concepts. In this case, if a concept-factor which is referred to the concepts that demand clinical examination is activated, then the correspondent check box will be activated, underlining that the result incorporates clinical examination and findings. Also, the weights change according to the symptoms' duration (days), allowing the system to reach faster to clearer decisions. Thus, the system can make an estimation for each time interval (day) and the doctor will be able to judge the results, taking into consideration the disease progress and making the final decision administering the necessary drugs.

As these two diseases are easily confused and they need different prescription, this tool can enhance or support the final decision. It is a dynamic and easily adaptable to changes tool, which allows triggering and/or activation of concepts.

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