Personalized Clinical Decision Support with Complex Hospital-Level Modelling

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Abstract
The paper presents the early results of the work aimed towards the development of the concept of clinical decision support system (CDSS). The concept is based on the complex hospital-level model for enhancement of the decision making process. The proposed conceptual architecture incorporates various classes of models and supports of the decision making for more complicated problems taking into account hospital-level activities. The proposed concept is now implemented in the CDSS at Federal Almazov North-West Medical Research Center.

Keywords: clinical decision support system, decision making, multi-agent system, information fusion, BigData

1 Introduction

Today personalized medicine is a widely used term with many interpretations [1]. The most popular one is involvement of personal analysis in the fields of genetics, proteomics, metabolomics etc. While these techniques are quite powerful and significantly extend the information available about the person under the investigation, it requires a vast amount of resources to perform and often has its limitation for decision support and treatment development. On the other hand, most of contemporary medical centers have a lot of information available for analysis: data stored in medical information systems, databases or plain files; personal notes of medical workers; surveys of patients etc. The analysis of all the stored data along with personal data provide a basis for decision support even with the use of explicit factors: phenotypic traits, behavioral analysis etc. Within the scope of decision support the integration of all the information sources still requires the solution for information fusion within the scope of situation assessment [2]. The information fusion approach considers the issues of
data integration, reduction and abstraction as well as user interaction in a context of situation awareness and assessment. On the other hand, integration and processing of large and diverse data requires the involvement of BigData approaches [3], which include the practices of the data distributed processing, model-based integration, and high-level descriptions of data analysis tasks.

One of contemporary directions of personalized medicine development is P4 medicine (personalized, predictive, preventive and participatory) approach [4]. The implementation of such approach requires integration of (a) simulation and modelling tools to predict the development of situations under various conditions and with different scenarios; (b) enhanced interactive tools for participation of the users of any kind; (c) procedures to optimize preventive measure within a context of situation assessment. Nevertheless, considering the process of clinical decision support it is often important not only to take into account the patient-level personalization (“who” is the person under the treatment) but also the facilities and characteristics of particular hospital (“where” the treatment is applied), individual skills and knowledge of the doctors (“by whom” the treatment is performed), particular real-life situation including all the related events and circumstances (“when” the treatment is applied). Consideration of the mentioned aspects stipulates the need extension of the decision support procedure with additional models, extended data sources, rules and conditions involving various scopes of treatment procedures, patient and hospital staff activities, hospital-level events etc.

Considering all these issues, we propose a basic approach for integration of various resources (data, information and knowledge sources; computational resources; modelling and simulation facilities) for complex support of decision making procedures extending regular “treatment-level” approach up to “hospital-level” approach within a P4 medicine scope. The approach is now being implemented within a decision support system for a set of cardiac diseases developed for Federal Almazov North-West Medical Research Center*.

2 Related Works

Decision support systems (DSS) with already existing clinical application, and also systems that are only under discussion are classified in the literature depending as a rule on the intended use, functionality, and approaches that have been used during system’s design and development [5], [6], [7].

Talking about some "canonical" clinical DSS (CDSS) would be incorrect. In general terms, it is an information system aimed to assist the clinician in making a decision [8]. The forms of assistance may vary from the rapid provision of context-sensitive disease- or drug-specific information to determination of the probable diagnosis for a particular patient. And the purpose of a specific CDSS determines the approaches that can be used in its development.

The aspiration to improve the quality of medical services, paradigms’ shift and development of technologies gives birth to new approaches to health care, the latter in turn provides a deeply personalized view at the patient [4].

At that, the volume of medical information has become so large that to store and analyze it without the help of computers is an overwhelming task. These circumstances stimulate the HIT-specialists to use data mining tools to meet the needs of the medical community and accelerate the dissemination of health information systems [9], [10].

At the same time, the problem of formalization and processing of the medical data remains topical. Patient data must be complete and adequate. It can be acquired in different ways: by using the keyboard or voice input, graphics processing, real-time wearable sensor systems etc. However, the problem is not exactly in acquiring the data, but in bringing it to a computer-understandable form. Even though there are standards on the description of the patient’s main conditions, it is impossible to

* http://www.almazovcentre.ru/?lang=en
describe the variety of clinical situations without certain additional means [5]. Methods of data formalization can be used at the stage of acquisition (structured input), nevertheless, this might create significant inconvenience. To satisfy the needs of medical professional in the best possible way, it is more suitable to use natural language processing techniques [11], [12].

The number of CDSS design principles is increasing rapidly. They can be classified only relatively due to the following reasons: a) often one principle is akin to the other and is intended to expand its capabilities, and b) even within the same principle, more of its implementations could be considered, each has its own characteristics. However, major groups of proven systems might be represented as follows [5], [6]:

- Probabilistic systems to forecast future development of the disease and to evaluate possibility of the specified diagnosis for particular patient. The clinician cannot be guided solely by the conclusions of such a system; however, it is a powerful supporting tool.

- Systems using artificial intelligence (AI) - their advantage over the probabilistic systems is that, in addition to statistical analysis, they are able to put forward a hypothesis about, for example, the possible relationship between the data and also can improve the quality of their work and learn while being used [6], [13].

- Branching logic systems are implemented as pre-defined workflows for each particular case or group of cases. Lacking sufficient flexibility, the actual situation frequently differs from the one predefined in the protocol. Nonetheless, branching logic systems proved to be efficient with the problems describing a set of actions that has never changed before. Such systems are often used as an element of a complex CDSS [5]. Moreover, having introduced certain modifications, a variety of possible strategies could be adopted. Adaptation to the real conditions makes them more flexible [14].

- Systems based on rules or knowledges, expert knowledge bases or a set of guidelines, escorted with mechanisms of inference engine. Absence of its own language to formalize existing knowledge and a set of relations between them, enable us to trace the chain of evidence leading to the conclusion. Its disadvantage is that the creation of far too complex rules and sophisticated relations between the rules significantly complicates its development.

- Ontology-driven DSS has in fact the same capabilities as the systems based on rules and systems based on the branching logic. Its databases of static knowledge, such as information on existing clinical protocols and treatment guidelines, and information related directly to the patient, allow us to consider the information about a patient information in the context of overall existing knowledge. Together with probabilistic system and a well-designed user interface it can become a powerful tool for obtaining comprehensive information about a particular patient and about the disease in general.

- Information support based on the context may be limited to a rapid provision of references and materials, such as currently available information about patient’s conditions, but at the same time it can be perceived more widely. Anything may be considered as a context, from clinical and medical history of a patient and up to the race, age, religion and so on. Anyway, this approach is of an auxiliary character.

It should be noted that talking about the superiority of one approach over another would be incorrect. Some are able to provide a deeper personalization, while others give a more accurate prediction, etc. Development of modern DSS often implies the use of different principles for different levels of the system architecture. Thus, the problem is not in bringing one of the approaches to perfection, but in the selection of a successful configuration that best provide support for decision-making [15].
Majority of relatively new techniques (case-based reasoning, Indentation-based decision support, etc.) eliminates the shortcomings of existing approaches making them a powerful tool for solving certain classes of problems [14], [15], [16]. Current level of human development draws the gaze towards modeling and simulation of physiological processes for a particular patient. Fantastic amounts of clinical data from a variety of sources (from electronic health records (EHR) to wearable sensors) stimulate the application of Data Mining methods to aggregation and analysis of these data. These results could be considered while choosing treatment not only for one patient, but for all similar patients. This abundance of ways of development implies that the user interaction with the system will go beyond a simple input-output to a more complex and sophisticated level.

Although the area of CDSS is wide and has a long, history most of the existing works are focused on the treatment procedure. Thus, development of a more complex generalized approach for CDSS building requires taking into account more complex processes on the level of whole hospital.

3 Extending CDSS Requirements

3.1 Decision Support in Medical Practice

Decision making process in clinical practice (usually performed by the doctors) is characterized by several features which affect this process significantly and distinguish it from decision making in many other areas. Firstly, decision is made on the basis of a large complex knowledge set which is weakly structured and contains contradictions. Moreover, this set of knowledge is constantly updating, the medical practices are changing (including reversal of the practices [18]). To work with the set of knowledge doctors have to make continuous efforts and spend their time to keep their knowledge up to date.

Secondary, the actual subject of the decision making is a patient (not a disease itself) which should be considered as person with history, habits, disabilities etc. [19]. All the above complicates the decision making process, as the same diseases may have different preferred treatment for different patients.

Then, the medical decision making involves a set of related areas which has direct influence on this process. Ethical issues are the ones of significant influence, especially in cases when decision is made under extreme circumstances or is bound to external limitations (rules, government recommendations etc.). Additionally the medical decisions and treatments are subject to particular laws and governmental decrees which set additional requirements and limitations to the decision making.

Next, medical decisions are constantly limited by time restriction depending on any particular disorder of the patient. For instance, a great deal of cardiac diseases may require decisions to be made within few minutes.

Finally, decision making is the area of personal responsibility of a particular doctors. Thus, taking into account the previously mentioned issues the decision is often made on the basis of personal experience and skills. It significantly effects the duration of differential diagnosis, since different hypotheses supported by various tests are being considered. So, one of the most important applications is to provide DSS for the doctors with a lack of experience in a particular field and with time constraints for decision making.

In addition, complexities of medical decisions become more significant when the uncertainties of various kinds are considered. Although any information, dataset, and evidence, doctors are faced with, are uncertain, but the decision should be unambiguous and specified. This contradiction may lead to “illusion of control” [19] while the results of the treatment are also characterized by uncertainty.
3.2 Hospital-Level Issues

To extend the decision support process out of the treatment-level several groups of issues can be considered:

- Core P4 medicine [4] which is defined as personalized, predictive, preventive and participatory medicine.

- Doctor-level personalization considers a set of experience and knowledge of particular doctors which are either decision makers or persons who apply treatments. The experience of the doctor can be an important subject to analysis and formalization (the experience may include work in different hospitals as an employee or consultant). Besides the knowledge and experience, this may include a) role of the doctor in the particular hospital with the list of accessible hospital facilities and interrelationships with other employees of a hospital; b) state in a particular moment of time with historical and planned events and duties in the hospital and outside of it; c) extended metadata of the doctor (marital status, age, etc.).

- Hospital-level features include a) information processing features in the hospital with particular technological facilities (medical information systems, data storages etc.); b) hospital facilities, medical equipment, available medicines etc.; c) staff of the hospital and the relationships between employees; d) floor plan of the building and movement of the people inside the hospital (patients, employees, visitors etc.); e) management of the hospital (global rules and decisions) including accounting; f) external requirements and limitations (governmental laws, recommendations etc.).

Consideration of the above mentioned aspects can extend the traditional decision support process (mainly focused on the treatment process) with a system-level view to the problem of personalized medicine. We believe that taking into account particular features of persons involved into treatment together with the hospital-level features can significantly improve the decision process.

3.3 Modelling and Simulation

One of the powerful ways to extend the CDSS capabilities is to hire modelling and simulation techniques to enrich the knowledge about the situation, involving stakeholders, upcoming events etc. Moreover the simulation model-based approach is almost the only way to predict the situation development. Within the proposed approach we consider the following set of models which can be incorporated into hospital-level DSS:

1. Physiological models to simulate a human body and its parts with the characteristics, obtained for a particular patient. These model can be used to obtain additional knowledge about the internal processes, to predict the development of the disease, to analyze different scenarios of the treatment (including surgeries) etc.

2. Data-based models aimed to analyze available datasets (including historical EHRs) to discover possible relationships and rules extending the predefined set of knowledge. This can be used to classify or rank patients and treatments, to search for similar cases, to prove the recommended treatment etc.

3. Agent-based hospital-level models to simulate indoor dynamics of the patients, hospital staff, visitors etc. These models can be applied to different scenarios: regular activity of the hospital (e.g. for the purpose of simulation of in-hospital infections); optimization of planned activities (e.g. transportation of the patients to the surgery); investigation of people dynamics in extreme events (e.g. escape in case of fire, actions in case of electric power failure).
4. Building information models to analyze hospital building structure and infrastructure. Being connected to the agent-based models these models extends their capability with dynamic simulation of crowd activities in particular complex building model.

5. Hospital-level information models considers data, information, financial and document flows within the hospital to develop of the complex models using above-mentioned models as building blocks or to providing them with appropriate input data and tests.

To consider the hospital-level complex model within a scope of CDSS development all these models should be taken into account. Being composed into the complex model of hospital-level activities they enables extension on P4 CDSS in a various ways.

4 Development of CDSS

4.1 Conceptual architecture

To support the development of CDSSs to answer the requirements discussed in Section 3, the high-level conceptual architecture (see fig. 1) was developed which can be used to implement various solutions in a scope of hospital-level investigation. The core goal of this architecture is to mention all the hospital-level informational artifacts (white rectangles) and models (gray rounded rectangles) which can be used in P4 CDSS keeping the eyes on the treatment process (as the main CDSS purpose).

The conceptual architecture is divided into three main layers. The hospital level incorporates high-level artifacts: information about hospital staff and facilities, financial management and metadata. All these information is aggregated within medical information system (MIS) which can be implemented in a various ways (even as a set of separated fine storages). The hospital-level information models controls flows of data and information stored in the MIS.

The agent level includes agent-based models supported by building models to simulate of in-door people dynamics. The information used for such simulation includes a) tracking of the agents in the hospital (using cameras, electronic keys etc.); b) building structure (floor plans, infrastructure, facilities placement etc.); c) patient-level activities including treatment procedures, surgeries, visiting of doctors etc.).
The core patient-centered activities form a loop where diagnosis stage is followed by the forecasting of the situation development. The forecast is used to develop the recommendations for the treatment. These activities with related patient-centered models (first of all, data-based and physiological modes) form a patient level. All the patient-centered activities and related datasets are stored in the MIS. The complex decision support in P4 CDSS enables support of the decisions made on each of the four mentioned patient-centered activities and involvement of various models to infer the decision with the use of the various information sources.

4.2 Data Analysis Architecture

One of the important issues within the CDSS is integration of various data and information sources along with the used models to solve the task of decision support. Fig. 2 shows the architecture of the data processing within the developed CDSS which was developed to answer both conceptual and technological requirements (proposed by the use case discussed in the next Section).

![Figure 2: Data analysis architecture](image)

The data processing architecture enables aggregation of data from various sources: stored in MIS, external storages or documents (including personal notes of doctors and nurses). The first stage of the data processing includes cleaning and unified formatting of the data. Then, on the data processing stage the data can be extended with the result of various models’ application (simulation results, data analysis results, machine learning procedures etc.) or knowledge-based extensions (e.g. discovering undocumented events by documented facts). The process of data management is controlled by data processing engine which controls models application, data transformation and preparation according to incoming queries. The engine is accessed by various applications and users including monitoring interfaces, DSSs, analytics workspaces, administrative staff applications, patients’ personal advisors etc. Knowledge plays a core role within the data processing architecture. It is acquired explicitly (from the experts) or implicitly (by the analysis of the presented data). The knowledge (rules, data models) is used to automatize the data processing and provide the users with actual appropriate datasets in an easiest way.

4.3 Technological background

This section briefly covers the original solutions which are planned to be used within the developed CDSS to solve various issues. To provide unified access to the various data sources with the ability to make high-level queries, the original technological platform for high-level BigData
analytics [20] will be used. It provides high-level dynamic domain-specific language (DSL) for querying the diverse data and processing it in the distributed storage of CLAVIRE cloud computing environment. This environment can be used to build workflow-based collaborative solutions for decision making which include simulation, data processing and user interaction parts [21]. To develop a hospital-level multi-agent models the original multi-scale Pulse engine [22] will be used.

5 Case Studies

This section presents a few early results of the implementation of the CDSS in the Federal Almazov North-West Medical Research Centre. Being one of the largest high-technology centers in Russia with a wide set of specializations: from cardiac surgery, transplantology, neurosurgery, oncohematology, to endocrinology and pediatrics. Several specializations and presence of research departments allow us to implement a multidisciplinary approach in practice. Internal work within the Almazov Centre is organized with the use of a MIS qMS† based on the InterSystems Caché database management system‡. This MIS is used as a basic data source within the developed CDSS, which can be extended with a set of documents and personal notes of doctors (often stored in the Microsoft Excel Spreadsheets).

Hospital-level analytics. The analysis of hospital-level statistics is mainly aimed towards the optimization of the hospital management. Nevertheless, it can be used to support the personalized decision making in case patient-centered activities are planned according to the global trends in hospital life. E.g. fig. 3 shows daily activities related to patient arrival rate and surgeries in the Research Centre.

Figure 3: Analytical view on statistical data about patients’ treatment for administrators (reanimation department of the Almazov Centre, 2014): (a) distribution of time spending at hospital after surgery; (b) distribution of arrival at hospital time; (c) heat map calendar showing number of surgeries per day

Personal treatment trajectory graph. In order to support decision making process for administrative management, the treatment trajectory graphs can be used. This kind of visualization perspective shows patient’s contacts with medical staff recovered from EMR in form of events in chronological order. The example in the fig. 4 presents the one treatment episode of patient with acute coronary syndrome (ACS). It could be seen that the patient had visited in total 92 different medical specialists in about a month. Relying on this kind of presentation, different patterns in data can be discovered, e.g. repeated visits, regular procedures etc.

† [http://www.sparm.com/products/qms](http://www.sparm.com/products/qms)
6 Conclusions and Future Works

This paper presents an early stage of the work aimed to the development of a general-purpose concept of the P4 CDSS rising from a treatment-level scope to a hospital-level scope. Within the proposed concept, the CDSS should be based on the complex model of the hospital enabling the inference of existing solutions for more sophisticated problems taking into account system-level view. The concept is based on complex data management considered from the point of view of the BigData and Information Fusion concepts. Emerging conceptual approaches are planned to be implemented in a CDSS for the Federal Almazov North-West Medical Research Centre and tested in decision making for several test cases and scenarios.

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