A History-based Algebra for Quality-checking Medical Guidelines

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Abstract. In this paper, we propose a formal theory to describe the development of medical guideline text in detail, but at a sufficiently high level abstraction, in such way that essential elements of the guidelines are highlighted. We argue that because of the fragmentary nature of medical guidelines, an approach where details in guideline text are omitted is justified. The different aspects of a guideline are illustrated and discussed by a number of examples from the Dutch breast cancer guideline. Furthermore, we discuss how the theory can be used to detect flaws in the guideline text at an early stage in the guideline development process and consequently can be used to improve the quality of medical guidelines.

1 Introduction

In order to control and improve the quality of medical care, organisations of medical professionals, such as medical specialists and nursing staff, are increasingly making use of evidence-based medical guidelines [8]. The goal of our work is to develop a representation of a guideline in detail, but at a sufficiently high level abstraction, in such way that essential elements of the guidelines are highlighted. As the ultimate aim is to verify properties and to study the quality of medical guidelines, the theory is necessarily formal in nature.

A major problem in achieving the ends mentioned above is that guidelines are fragmentary, which renders it hard to formalise them, as one way or the other, the gaps have to be filled in, or the modelling language should allow omitting detail. The former approach is often used in guideline modelling languages such as Asbru [6] and GLIF [5] which represents a guideline as a program-like structure. In that case, program verification techniques can be used to investigate properties of the original guideline. In this article, we take the latter approach, which is the main reason why we have decided to abstract from the details of a guideline text. Other, more logical oriented approaches such as PROforma [2], which also allow fragmentary formalisation of guidelines are different in the sense that we concentrate on the medical knowledge concerning patient-groups and ultimately on the composition of a guideline rather than the decision making. This results in different design choices.

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2 Framework for Modelling Medical Guidelines

2.1 Basic Elements

Time  Time is used in a guideline to model the changes in situation of the patient and its environment. Research has shown that an imprecise time axis is sufficient in most cases. However, sometimes guidelines are more specific and actually give reasonably precise time frames, but only in a limited number of cases medical science is as precise as physics. Hence, a formalisation of time should allow for an extension of the cause-consequence relationship. Consequently, we assume there is a set \( \text{Time} \) and a relation \( \preceq : \text{Time} \times \text{Time} \) such that \( \preceq \) is reflexive and transitive, i.e., \( \preceq \) is a pre-order. Note that \( \preceq \) is not anti-symmetric in general, because there can very well be different descriptions of the same points in time. Moreover, we do not assume that this ordering is known, but in general there are known constraints with respect to this order.

State  A state can provide a description of the actual situation of a patient given all known facts and more general situations of individual patients. The traditional technique to abstract from a certain situation (a model) is by providing a logical language that refers to one or more situations without fixing all the details. Typical elements in the state of a patient are symptoms, signs and other measurable elements. Because many of these elements are unknown and often irrelevant we have chosen to define the state space as a many-sorted first order logic \( \text{State} \) including equality, but excluding any free variables. Let there be a structure \( \mathcal{A} \) consisting of a domain for every sort \( \sigma \) and an interpretation \( I \) of every constant of a given sort to the domain of this sort such that \( I(c^\sigma_i) \neq I(c^\sigma_j) \) where \( i \neq j \) or \( \sigma \neq \sigma' \), i.e., we assume unique names. Let \( \text{State} \) be a language built up inductively consisting of terms and propositional connectives in the traditional manner (see for example [3]) such that elements of \( \text{State} \) can be interpreted on the structure. For example, typically temperature = 37 \( \lor \) systolic-blood-pressure = 120 is an element of \( \text{State} \). Note that in the upcoming sections we will leave the different sorts implicit.

Intervention  Interventions include medical actions that influence the condition or the environment of a patient. The domain of interventions is formalised as a countable set \( \text{Interventions} \). The interpretation of a subset of the \( \text{Interventions} \) is a treatment where each intervention is applied, either in sequence or in parallel. Furthermore, we have a closed-world assumption for each set of interventions \( I \) which says that if \( i \notin I \), then intervention \( i \) is not applied.

2.2 Histories

A medical guideline contains descriptions of processes concerning the disease, medical management and recommendations. Static descriptions of the different aspects of patient groups as we have described above are captured in a history.

Let \( \wp(X) \) denote the powerset of \( X \) and let \( [V \rightarrow W] \) denote the function space of functions \( f : V \rightarrow (W \cup \{\epsilon\}) \), where \( \epsilon \) will have the interpretation
‘undefined’. Let a time constraint be of the form \( t \preceq t' \) or \( t \not\preceq t' \). A model of a set of constraints is a total pre-order. A history is defined as an element of the set \( \text{History} \) such that \( \text{History} = \{ \text{Time} \rightarrow \{ \text{State} \times \varphi(\text{Intervention}) \} \} \) in combination with a set of time constraints \( \mathcal{C} \).

The examples we present here were extracted from a medical guideline regarding breast cancer by CBO [1], an institute that has supported the development of most of the guidelines developed so far by the Dutch medical specialists.

**Example 1.** After a mastectomy or breast-conserving treatment, there is an increased risk of movement problems, impaired sensation, pain, and lymphoedema. Adjuvant radiotherapy increases the risk of limited movement of the shoulder and of lymphoedema. Physiotherapeutic intervention can have a positive effect on the recovery of mobility and functionality of the shoulder joint. Early initiation of intensive remedial therapy (in other words, during the first postoperative week) has an unfavourable effect on the wound drainage volume and duration.

There are several possible ways to formalize this excerpt depending on the focus of the modeller. One possibility is to pick some patient-group, for example the patient-group which receives physiotherapy too early after the mastectomy. We can denote this history \( h \) algebraically as follows.

\[
h = \{ (t_0, \text{breast cancer}, \emptyset), (t_1, \text{breast cancer}, \{ \text{mastectomy} \}), (t_2, \text{lymphoedema}, \emptyset), (t_3, \text{lymphoedema}, \{ \text{physiotherapy} \}), (t_4, \text{high drainage}, \emptyset) \}
\]

Note that these elements of \( \text{Time} \) do not express anything about the distance between the time points. So the distance between \( t_0 \) and \( t_1 \) is not necessarily the same distance as the distance between \( t_1 \) and \( t_2 \). In addition to being imprecise about certain patients it also allows us to ‘instantiate’ patients of a certain patient-group by adding patient-specific information to this history.

### 2.3 Expectations

When dealing with guidelines, we are concerned with the dynamic aspect, for example, the description of how a history is expected to continue. As a consequence, this means that the history is extended with new information. A typical example is an expectation of a treatment, i.e., the expected history that a certain treatment yields. We formalise this notion below.

Given a history \( h \) and \( h' \) then \( h' \) is an extension of \( h \) if \( \text{dom}(h) \subseteq \text{dom}(h') \) and for all \( t \in \text{Time} \): \( h(t) \neq e \) implies \( h(t) = h'(t) \). The projection of a history \( h \) to two elements \( i, j \in \text{Time} \), denoted as \( \langle h \rangle_{(i,j)} \), is defined as the history \( h' \) such that: (1) \( \text{dom}(h') \subseteq \text{dom}(h) \), (2) for all \( t \in \text{Time} \): \( h(t) \neq e \) implies \( h(t) = h'(t) \) and, (3) \( t \in \text{dom}(h') \Rightarrow i \preceq t \preceq j \). Obviously, a history is always an extension of a projection on itself. The expected continuation of a given history is the function space \( \mathcal{E} = \{ \text{History} \rightarrow \varphi(\text{History}) \} \) such that for each \( e \in \mathcal{E} \) and \( h \in \text{History} \) the following hold: (1) \( e(h) \neq \{ h \} \) (the expectation introduces new information), (2) \( h' \in e(h) \Rightarrow h' \) is an extension of \( h \) (no information is lost) and, (3) let \( m \in \min(\text{dom}(h)) \), \( M \in \max(\text{dom}(h)) \), \( i \geq M \): \( e(h) \supseteq \bigcup_{h' \in e(h)} e(\langle h' \rangle_{m,i}) \) (the expectation function is...
consistent with respect to its own expectations). For example, consider a patient with breast cancer \( p \) where \( p = \{ (t_1, \text{breast cancer}, \{ \text{chemo-therapy} \}) \} \). The use of chemo-therapy can cause an infection, which we can describe as an expectation \( e(p) = \{ h \} \) where \( h = \{ (t_1, \text{breast cancer}, \{ \text{chemo-therapy} \}), (t_2, \text{infection}, \varnothing) \} \).

Note that this is of course a rather naive example, because in this case we can, by definition of an expectation function, deduce that \( e(e(p)) = e(p) \). In a more realistic setting, more alternatives would be listed, such that this simple relation does not hold.

3 Application to Fragments of Medical Guidelines

As an application to check the quality of a guideline we consider its consistency. Because of the commitment of guideline developers to produce high quality guidelines, we do not expect to find blatant inconsistencies within a guideline. Nonetheless, it is expected that during the process of developing guidelines different views on how the patient should be treated are considered. Clearly, in many cases these views will be inconsistent and it is therefore of great use to detect these inconsistencies.

Every country typically develops their own version of a guideline about similar subjects. Therefore, we have the possibility to simulate the process as described above by comparing recommendations of different guidelines. We have chosen to compare the Dutch CBO guideline with the Scottish SIGN guideline for breast cancer [7]. Consider chapter 13.2 of this guideline concerning local recurrence in the axilla after mastectomy.

Example 2. Nodule(s)/nodes should be excised (...) and if not previously irradiated, locoregional radiotherapy should be given.

Thus, the following patient-group is consistent, and it can be argued this is implied by a closed world assumption that is taken to hold in many medical applications, with the SIGN guideline:

\[
h = \{ (t_0, \text{breast cancer}, \{ \text{mastectomy} \}), (t_1, \text{breast cancer}, \{ \text{radiotherapy} \}), (t_2, \neg \text{breast cancer}, \varnothing), (t_3, \text{breast cancer}, I) \}
\]

such that \( t_0 \prec t_1 \prec t_2 \prec t_3 \) and radiotherapy \( \notin I \). The more recent CBO guideline discusses the local treatment of local recurrence following modified radical mastectomy.

Example 3. If an isolated local recurrence occurs in a previously irradiated area, high-dose radiotherapy is not an option. In that case, low-dose re-radiation with hyperthermia is the treatment of choice.

Hence, in this case we find that there are patient-groups which are treated taking this guideline into account described by:

\[
h' = \{ (t_0, \text{breast cancer}, \{ \text{mastectomy} \}), (t_1, \text{breast cancer}, \{ \text{radiotherapy} \}), (t_2, \neg \text{breast cancer}, \varnothing), (t_3, \text{breast cancer}, \{ \text{radiotherapy, hyperthermia} \}) \}
\]

such that \( t_0 \prec t_1 \prec t_2 \prec t_3 \). Hence, we find by definition that \( h \) and \( h' \) are inconsistent. In particular, we find that these fragments are inconsistent with respect to their interventions.
4 Discussion

We have presented a framework for quality-checking of medical guidelines. Use was made of algebraic theory and insights that we have gained during formalisation of a part of the Dutch breast cancer guideline. In our previous work [4], a method was presented for verifying parts of a medical guideline using temporal logic and abduction in the context of theorem proving. The framework presented here allows for more realistic and elaborate modelling of the guideline, while preserving the advantages of a formal model such as the possibility to use abduction and automated theorem proving for its verification.

Like in many other guideline description languages, time has a central role in our approach. There are important differences however. One of the main differences is that time is inherently less precise than in other languages. For example, in PROforma or Asbru, to refer to imprecise time points, one must use time intervals. However, these intervals are defined by exact time points and while this is imperative to create a task hierarchy or even to schedule the tasks in a consistent manner, we argue it is not imperative to have this information to check many of the quality criteria of a medical guideline.

In our future work we will extend the theory in a number of ways. Firstly, more high-level methods are being developed that allow the characterization of a history, either by embedding histories in a logical language or by defining certain patterns in histories, e.g., a history with a monotonically increasing parameter. Secondly, we will work towards establishing a formal relation between histories, or expectations that people have of treatment and processes that occur within a patient on one hand and recommendations on the other, i.e., the construction of a guideline.

References