Operationalizing Prostate Cancer Clinical Pathways: An Ontological Model to Computerize, Merge and Execute Institution-Specific Clinical Pathways

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Abstract. The computerization of paper-based Clinical Pathways (CP) can allow them to be operationalized as a decision-support and care planning tool at the point-of-care. We applied a knowledge management approach to computerize the prostate cancer CP for three different locations. We present a new prostate cancer CP ontology that features the novel merging of multiple CP based on the similarities of their diagnostic-treatment concepts, whilst maintaining the unique aspects of each specific CP, to realize a common unified CP model. In this paper we will highlight the main components of our prostate cancer CP ontology, and discuss the concept of CP branching and merging nodes. We conclude that our computerized CP can be executed through a logic-based engine to realize a point-of-care decision-support system for managing prostate cancer care.

1 INTRODUCTION

Prostate cancer is the most common type of cancer among Canadian men, with an estimated 22,300 newly diagnosed cases and 4,300 deaths in Canada in 2007 alone. In the Canadian healthcare system, the diagnosis and treatment of prostate cancer follows an integrated approach involving multiple disciplines dispersed across multiple care setting and engaging multiple health professionals with different specialities and roles. This integrated approach demands an effective partnership between various disciplines such as family medicine, urology, radiation oncology, nursing, and psychological support resources. Despite the clinical significance of such an integrated approach, its on-the-ground implementation presents various challenges, such as (a) how to navigate and manage a patient's care activities throughout the longitudinal care trajectory? and (b) how to coordinate the respective activities of the different care providers in a timely and efficient manner?

In an attempt to support the coordination and integration of healthcare services spanning multidisciplinary settings and care providers, healthcare institutions develop Clinical Pathways (CP) as a means to both chart and streamline the diagnostic-treatment cycle. CP are evidence-based patient care algorithms/charts that describe the care process for specific medical conditions within a localized setting [2]. At present, most CP are paper-based and therefore cannot be conveniently shared and directly deployed at the point-of-care, regardless of the location of the patient and the attending care provider. We argue that the computerization of paper-based CP can help to operationalize them as (a) point-of-care clinical guide; (b) patient information sharing medium between different care providers; (c) patient navigation and care coordination tool; and (d) a decision-support tool to help provide standardized, timely, cost-effective and safe clinical care to prostate cancer patients [1].

In this paper we present our knowledge modeling work leading to the development of a prostate cancer care planning and management system. The overall project involves three phases: (i) the development of prostate cancer CP for three different Canadian cancer care institutions in Halifax, Winnipeg and Calgary. In this knowledge engineering phase, oncologists, urologists and nursing experts were engaged to elicit the CP in their respective institutions, thus yielding three location-specific prostate cancer CP; (ii) the modeling of the CP knowledge in order to computerize and subsequently execute the CP (with patient data) at the point-of-care. We present our ontology-based knowledge modeling approach that led to the development of a comprehensive OWL-based prostate cancer care ontology. The feature of our modelling approach is that it allows the merging of these location-specific CP along common processes, actions and recommendations; and (iii) the execution of the ontologically-modeled CP using a logic-based execution engine that connects with a patient-data source to guide both the respective care-provider and the patient through the prostate cancer care pathway.

In this paper we will describe our ontology based CP knowledge modeling approach and highlight the novel merging of the three location-specific CP into a single computer-interpretable model. We will highlight the main components of ontology, especially the merging and branching nodes introduced within our CP ontology. We will demonstrate that an ontology based CP representation allows the instantiation of three paper-based prostate cancer CP and in turn yields an executable CP.

2 PROSTATE CANCER CLINICAL PATHWAYS

In this project we developed prostate cancer CP that illustrates activities concerning the diagnosis, management and follow up of prostate cancer patients at three different locations–i.e. Halifax, Calgary and Winnipeg regional health setting. Each location-specific CP characterizes the following: (a) Organizational level processes to be enacted by a team of multidisciplinary actors; and (b) Patient management processes that require a specialized care team member to perform a specific action on the patient. A systematic organization of this information yielded a prostate cancer CP as a flowchart that contains four main components–namely *actions*, *decisions*, *branching/merging nodes* and *recommendations/plans* (see figure 1).

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All three location-specific CP were divided into four consultations, where in each consultation a set of tasks were performed by an identified team member(s) to achieve a defined outcome. Each CP begins with a consultation by a family physician and concludes with a consultation with an urologist to determine treatment options and follow-up routines. For each consultation, the CP records the stipulated clinical practices and care resources in terms of the sequencing, decision criterion, time intervals, actors, expected outcome and recommendations associated with specific care tasks that need to be performed during a consultation. It was interesting to note that despite certain variations, the three CP exhibited a good deal of overlap at the task-level, thus vindicating that these CP conform to widely accepted Canadian practices for prostate care. The overlap between the CP allowed us to pursue the **merging** of the different CP to create a common unified location-independent CP that distinguishes between a set of tasks common to all locations, whilst allowing location-specific branches to model those tasks that are unique to a particular location.

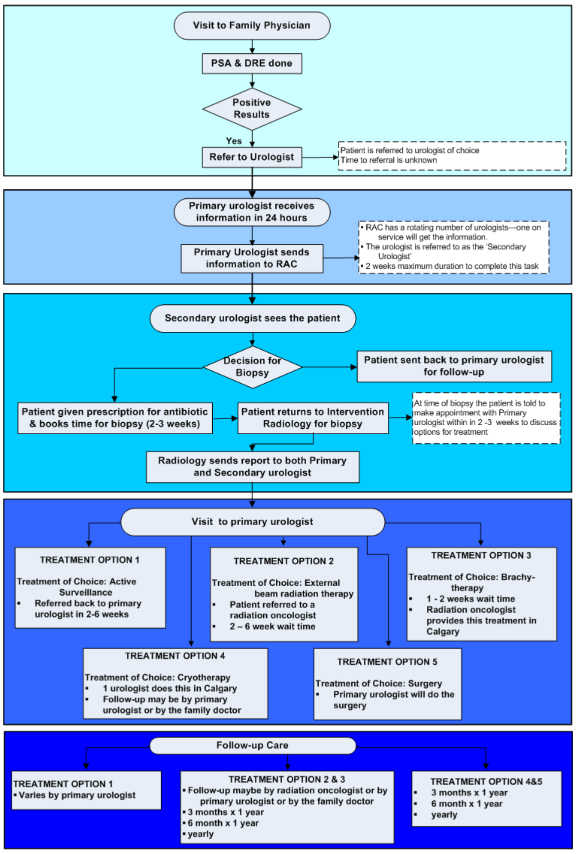

Figure 1. Prostate Cancer Clinical Pathway for Calgary

3 KNOWLEDGE MODELING APPROACH FOR COMPUTERIZING CLINICAL PATHWAYS

Knowledge modeling involves the abstraction of domain-specific knowledge in terms of concepts that encapsulate the domain knowledge, problem-solving behavior, operational processes, and functional constraints. In healthcare, domain-specific knowledge is captured in terms of clinical practice guidelines, clinical pathways and research articles. For this project, the three location-specific prostate cancer CP served as the domain knowledge artifacts.

We adopted a knowledge management approach, in particular the use of Semantic Web technologies for modeling the domain knowledge in terms of an ontology [5]. Our prostate cancer ontology captures the salient diagnostic, treatment and operational concepts, and relates these concepts using semantic and pragmatic relationships to form a prostate cancer knowledge model. We used a middle-out approach for ontology engineering [4], whereby the knowledge model is iteratively developed-i.e. starting from generic to specific concepts and relationships–using the three prostate cancer CP. Instead of modeling each CP as a unique model, our CP modeling approach focused on ways to **merge** the three different location-specific CP to realize a unified ontological model for prostate cancer CP. The rationale for merging CP is to create a flexible knowledge model that not only responds to the clinical or administrative events in the care process, but also factors the various constraints, such as the location of the patient, when discharging recommendations/actions. Technically speaking, the ability to merge the CP in a flexible yet semantically and pragmatically correct knowledge model was the main knowledge modeling challenge [3]. CP merging was pursued by modeling the task-level similarities between the three CP as a single common ontology, however whenever we encountered a point when a location-specific CP was pursing a unique set of tasks we created a branch ontology to model the unique task, treatment or follow-up options practiced at a specific location. A branch ontology proceeds along a location-specific path until it reaches a **merging node**–i.e. a task or a plan that is common to all locations–that allows multiple branches to merge to once again realize a common path modeled by the overall *common ontology*. In this way, we developed a novel CP modeling approach that allowed multiple CP from the same domain to be jointly modeled whilst maintaining the unique behaviors of independent CP. Figure 2 shows a schematic of a unified CP for three different sites that includes both branching and merging nodes.

4 A PROSTATE CANCER CLINICAL PATHWAY ONTOLOGY

We used the Web Ontology Language (OWL) via the ontology editor Protégé to develop our prostate cancer CP ontology. The entire specifics of our CP ontology are beyond the scope of the paper, yet below we present its salient aspects. Class names are denoted using UPPERCASE, relationships with *Italics* and individuals within 'quotation marks'.

4.1 Descriptions of the classes and their individuals

Our ontology begins with class PLAN which corresponds to all four consultations with a team of multidisciplinary CLINICIANS. DECISION-CRITERIA models the choices to be made in order to reach the next step, for instance the individuals 'between 4 and 10' and 'greater than 10' are used as decision criteria for a decision-node 'PSA/FreeTotalPSA' which is an individual of INVESTIGATION. The evaluation of DECISION-CRITERIA results in either a TASK to be performed or a TEST-RESULT to be generated. TASK represents the different care tasks performed by the care team. TASK is further classified as CONSULTATION-TASK, NON-CONSULATION-TASK, REFERRAL-TASK and FOLLOW-UP-TASK. The class FOLLOW-UP represents follow-up visits after each treatment option, e.g. 'FirstPostSurgeryFollowUp'. To control the execution of the pathway, we have defined a class TERMINATION-TASK as

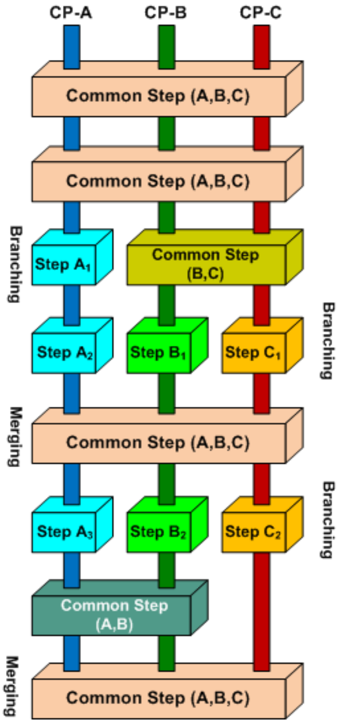

Figure 2. A unified prostate cancer CP with branching and merging nodes

a sub-class of TASK, which has two individuals 'PathwayEnds' which specifies the end of the CP and 'TaskEnds' which represents the end of a task. A PLACE is further categorized into CARE-SETTING with exemplar individual being 'RapidAccessClinic', and PATHWAY-REGION with exemplar individuals 'Calgary', 'Halifax' and 'Winnipeg'. PATIENT-CONDITION-SEVERITY specifies the condition of the patient as being 'Urgent', 'Concerned' and 'NonUrgent'. TREATMENT represents treatment options, for instance 'ActiveSurveillance', 'Brachytherapy' etc. INVESTIGATION captures diagnostic tests, e.g. 'Biopsy', 'PSA/FreeTotalPSA'.

4.2 Modeling of temporal concepts in the CP

The temporal concepts in the CP are represented by three classes:

1. INTERVAL-EVENT which defines an interval between activities or wait before a particular task, as a named event, e.g. wait interval for surgery
2. INTERVAL-DURATION which defines the duration of an interval event, e.g. six to eight week which is wait time for surgery. Another temporal constraint inherent in a CP is the frequency of activities within a task.
3. FREQUENCY depicts the frequency of the follow-up activities noted in the prostate cancer CP, for instance to represent the concept EveryThreeMonths. Preserving FREQUENCY as a separate class ensures that future changes or addition to frequency of an activity can be easily incorporated in the model.

4.3 Description of the relationships between the classes

Our prostate cancer CP ontology models a large number of relationships between classes; here we present some salient relationships. PLAN, TEST-RESULT and PATIENT-CONDITION-SEVERITY have relation *isFollowedByTask* with TASK, because an individual of any of these classes is followed by a TASK. For example, if PATIENT-CONDITION-SEVERITY is 'NonUrgent' then it *isFollowedByTask* 'BiopsyIsNotBookedWithSecondConsultation'an individual of CONSULTATION-TASK. A task can be followed by another task, therefore TASK has the relation *isFollowedByTask* with itself also. TASK, TREATMENT and FOLLOW-UP have relationship *hasInterval* with INTERVAL-EVENT, eg. 'ReferToUrologist' as an individual of REFERRAL-TASK with *hasInterval* to represent 'TimeToReferToUrologist' which is an individual of INTERVAL-EVENT. TREATMENT is related to FOLLOW-UP via *hasfollowUpCare*. A follow-up might refer to follow-up task(s), therefore FOLLOW-UP is related to TASK via *hasTask*. For example 'FirstPostSurgeryFollowUp', which is an individual of FOLLOW-UP *hasTask* 'RemovalOfStaples' which is an individual of FOLLOWUP-TASK. TASK and FOLLOWUP have relationship *isFollowedBy* with FOLLOW-UP as its range. For example the TASK 'RemovalOfStaples' *isFollowedBy* 'SecondPostSurgeryfollowUp' which is an individual of FOLLOW-UP. In turn, 'SecondPostSurgeryFollowUp' *hasTask* 'RemovalOfCatheter' which *isFollowedBy* 'ThirdPostSurgeryFollowUp' which is an individual of FOLLOW-UP. A snapshot of this scenario is shown in figure 3.

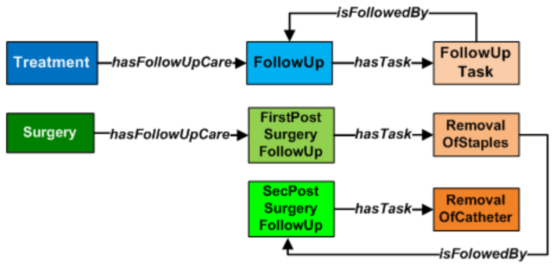

Figure 3. Interrelationships between the classes TREATMENT, FOLLOW-UP and TASK

5 MODELLING MERGING AND BRANCHING WITHIN THE CP ONTOLOGY

We have developed a single prostate cancer CP ontology that is able to uniquely model the independent characteristics of all the three different CP. Our modeling approach allows the merging of the three location-specific CP into a unified CP ontology based on the commonality of their inherent concepts at the level of clinical pragmatics. Yet, in order to model the non-overalpping concepts between the CP we have introduced a **branching** function/node that allows an independent CP to pursue tasks specific to it. And, through a **merging** function/node we allow the branched CP to once again merge with other concurrent CP to realize a high-level unified CP ontology. Figure 2 earlier presented the concept of CP merging and branching.

5.1 Branching based on decision criteria

In our CP ontology certain individuals of classes INVESTIGATION, TASK and FOLLOWUP can also be regarded as **decision nodes** in a CP, therefore these classes are related to class DECISION-CRITERIA through relationship *hasDecisionCriteria* (as illustrated in figure 4). As mentioned earlier, the class DECISION-CRITERIA models the available choices (or paths) when determining the next step–one of the given choices is selected (based on user input) in order to proceed to the next specified step. We explain this concept through an example illustrating how next step choices are handled in our ontology. Consider 'TakePatientConsent' (an individual of CONSULTATION-TASK) as a decision node in the CP, with two possible choices–i.e. 'PatientGivesConsent' and 'PatientDoesNotGiveConsent' (individuals of DECISION-CRITERIA) as the set of potential values for the relation *hasDecisionCriteria*. During execution, when we arrive at the above-mentioned decision node we need to select one of these choices in order to direct the flow of the CP in a particular direction, which is modeled by TASK through property *hasAction*–note that DECISION-CRITERIA is related to TASK through property *hasAction*. Suppose, in response to the value 'TakePatientConsent' the relation *hasDecsionCriteria* gets the value 'PatientGivesConsent', then the value for the next*hasAction* relation will be 'BookBiopsyWithSecondConsulation', on the other hand if value for *hasDecisionCriteria* is 'PatientDoesNotGiveConsent', then the value for *hasAction* will be 'DoNotBookBiopsyWithSecondConsutation'. In this way we are able to model branching effects within a CP based on decision nodes.

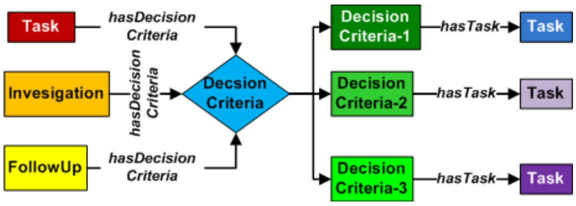

Figure 4. Modeling of decision criteria

5.2 Branching based on location

Another type of branching involves a CP diverging from the unified ontology based on the location of the patient for a given task, treatment or follow-up options. We model this behavior through **branching nodes** that denote an intersection between two classes to represent a unique individual that is the function of two intersected classes. We have developed three unique classes–i.e. REGION-TASK-INTERSECTION, REGION-TREATMENT-INTERSECTION and REGION-FOLLOWUP-INTERSECTION that serve as branching nodes based on location. The REGION-TASK-INTERSECTION represents an intersection between REGION and TASK to signify a a unique individual, such as a unique TaskA that is perfomed at RegionB. Likewise, REGION-TREATMENT-INTERSECTION will have an individual that is a unique TreatmentX that is offered in a specific region. Note that if TreatmentX was common for all three regions then there was no need to use an intersection o denote a branch, rather TreatmentX would have been part of the unified CP. The branching nodes have relations *hasLocation*, *hasTask*, *includeTreatmenOptions* and *hasFollowUpCare*. REGION-TASK-INTERSECTION has an object property *isFollowedByConsultation*, the range of which is class PLAN, to represent the possibility that a task at a particular location can be followed by a new consultation as opposed to a task. These relationships were carefully determined to ensure that we always have unique individuals of the classes based on the combination of the values of these relationships. For example, an individual of any of the classes PLAN, TASK, PATIENT-CONDITION-SEVERITY and TEST-RESULT can be followed by a task that is specific to a certain location only, thus initiating the branching of that particular segment of the location-specific CP from the unified CP.

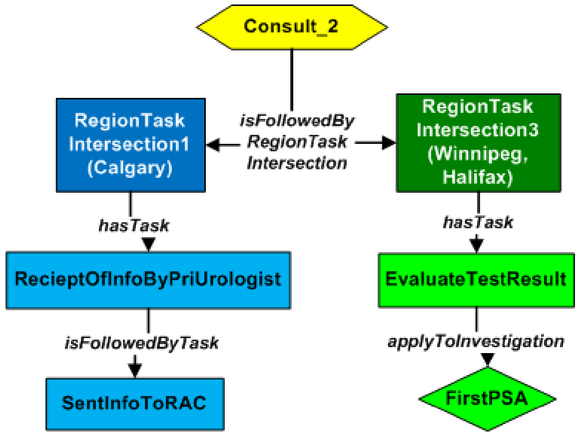

Figure 5. Branching of CP at the level of Consultation-2

We explain the concept of branching using intersections through the following example, also depicted in figure 5. In the three CP, it is noted that the activities following consultation-2 are different, such that the tasks in Calgary are different from the ones in Winnipeg and Halifax So during CP execution, when a patient enters 'Consultation-2' which is an individual of PLAN, the next task in this plan depends on the location of the patient. This is modeled by PLAN having a relation *isFollowedByRegionTaskIntersection* which in this case has values 'RegionTaskIntersection-1' and 'RegionTaskIntersection-3', both of which are individuals of the branching node REGION-TASK-INTERSECTION. At this point, the unified CP is divided into two branches–one branch for Calgary and the other one for Winnipeg and Halifax. The first branch is modeled by the individual 'RegionTaskIntersection-1' (of REGION-TASK-INTERSECTION) that has 'Calgary' as the value for *hasLocation*, and the unique task is 'RecieptOfInformationByPriUrologist' as the value for *hasTask* relation. The second branch is modeled by the individual 'RegionTaskIntersection-3' that has 'Halifax' and 'Winnipeg' as the value for *hasLocation*, and it has 'EvaluateTestResult' as the value for the *hasTask* relation. In this way, we were able to represent the unique activities at a specific location whilst maintaining a common CP structure representing the overlapping activities. It may be noted that these two branches may subsequently merge during the CP execution to realize a unified CP (as shown in figure 2).

5.3 Merging of the different CP branches

The merging of different CP is possible at the level of common tasks or plans. As stated earlier, if a CP branches off then a merging node allows it to merge back with the unified CP if (a) no further activities are left in the branch; or (b) the next activity is a common task or consultation. In figure 6, we illustrate an example of a merging node, whereby during 'Consultation-3' after the task 'RecieptOfBiopsyReportByUrologist' the CP ontology models three separate location-based branches because at each location the following task is different. All the three branches are individuals of REGION-TASK-INTERSECTION, namely 'RegionTaskIntersection-9' that *hasLocation* ‘Halifax’, ‘RegionTaskIntersection-10’ with *hasLocation* as ‘Calgary’, and ‘RegionTaskIntersection-12’ with *hasLocation* having ‘Winnipeg’ as the individual value. These branches have unique individuals for *hasTask* and *isFollowedByConsultation* relations. However, as shown in figure 6, later on these branches converge on ‘Consult-4’ (an individual of PLAN) which serves as a merging node to once again realize a unified CP. Note that in Calgary the task ‘RecieptOfBiopsyReportByUrologist’ is followed directly by ‘Consult-4’, while in Winnipeg the task before the merge is ‘EvaluateBiopsyReport’. This task is a decision node where the pathway branches again depending on the result of the biopsy report; if the result is positive then the branch will converge at ‘Consult-4’.

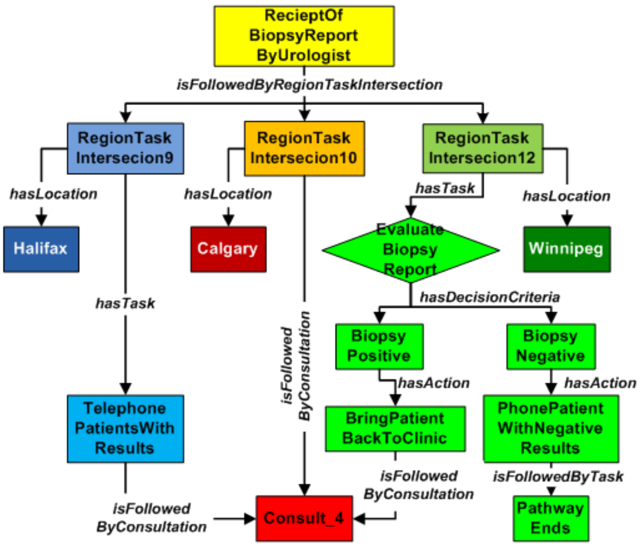

Figure 6. Merging of three branches at Consultation-4

6 MODELING OTHER CP INTERSECTIONS

Our CP ontology accounts for the eventuality that there might be additional location related CP variations concerning the team member performing a task, time interval between the tasks and frequency of an activity within a task. We have modeled such potential CP variations noted when the classes CLINICIAN, INTERVAL-DURATION and FREQUENCY intersect with location. The resulting intersection are REGION-CLINICIAN-INTERSECTION, REGION-INTERVAL-INTERSECTION, REGION-FREQUENCY-INTERSECTION. To REGION-CLINICIAN-INTERSECTION accounts for the possibility that a specific TASK, TREATMENT or FOLLOWUP can be performed by a different clinician at a specific region. Our CP ontology relates these classes to REGION-CLINICIAN-INTERSECTION with an object property *hasRegionClinicianIntersection*. Each individual of this class is guaranteed to be unique through the relations *isPerformedBy* and *applyToClinicalSetting* which have ranges CLINICIAN and CARE-SETTING, in addition to the relation *hasLocation*. These properties allow expressing different combinations of location, clinicians and care-care-setting as unique individuals of class REGION-CLINICAN-INTERSECTION. An individual of TASK, TREATMENT or FOLLOW-UP can then have a unique relationship in terms of location of the patient, a certain type of clinician who is going to perform a task, in a particular care-setting. Similarly an individual of INTERVAL-EVENT through the relation *hasRegionIntervalIntersection* can have a particular interval duration depending on the location of the patient. It may be noted that we do not regard these intersections as branching nodes in a strict sense because they do not lead to separate CP branches.

7 CONCLUDING REMARKS

We presented a prostate cancer CP ontology that allows the computerization and execution of a location-specific CP to manage, plan and streamline the prostate cancer care activities. We presented a novel modeling approach that first established commonalities in the care processes across the three different regions and then attempted to merge these individual location-specific CP, at the medical and pragmatic levels, to realize a high-level prostate cancer CP ontology that unifies the three different CP. The development of a common unified knowledge model, in this case to represent CP, allows for (a) improved sustainability of the model to handle future additions and updates; (b) generalizability of knowledge across different regions; and (c) identification of specialized tasks at each location. This information would have been lost if each CP was modeled as a unique entity, and we would have lost the opportunity to streamline and standardize the care process across different regions. At the same time introspecting location-specific branches provides CP developers some insights as to the why some regions are doing things differently and measuring the outcomes of these branches may serve as a guiding principle for development of more optimal CP for other regions. For instance, we identified that the different prostate cancer CP tend to branch out at the Task, Treatment and FollowUp aspects subject to the location of the patient, and that the different location-specific CP branches merge at the Task and Plan aspects of a CP. From a modeling standpoint, we introduced the concept of branching and merging nodes in concert with various inter-class intersections to model unique CP branches or node-specific variations. The ontology has been evaluated for semantic correctness and completeness by instantiating the three prostate cancer CP. These computerized CP can now be executed, when connected with patient data, through a simple logic-based reasoning engine or a workflow engine. This has been achieved by establishing a series of interrelations between classes using object properties–i.e. in our CP model each task identifies the following activity thus allowing a sequential execution of the CP. Our future work involves the computerization of additional prostate cancer CP by instantiating them within our CP ontology. We are in the final stages of developing a web-based prostate cancer care management system, based on the CP ontology, to streamline prostate cancer care at the three Canadian cancer care facilities.

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