Development and evaluation of methods for structured recording of heart murmur findings using SNOMED CT® post-coordination

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ABSTRACT

Objective: Structured recording of examination findings, such as heart murmurs, is important for effective retrieval and analysis of data. Our study proposes two models for post-coordinating murmur findings and evaluates their ability to record murmurs found in clinical records.

Methods: Two models were proposed for post-coordinating murmur findings: the Concept-dependent Attributes model and the Interprets/Has interpretation model. A micro-nomenclature was created based on each model by using the subset and extension mechanisms provided for by the SNOMED-CT® framework. Within each micro-nomenclature a partonomy of cardiac cycle timing values was generated. In order for each model to be capable of representing clinical data, a mechanism for handling range values was developed. One hundred murmurs taken from clinical records were entered into two systems that were built based on each model to enter and display murmur data.

Results: Both models were able to record all 100 murmur findings; both required the addition of the same number of concepts into their respective micro-nomenclatures. However, the Interprets/Has interpretation model required twice the storage space for recording murmurs.

Conclusion: We found little difference in the requirements for implementation of either model. In fact, data stored using these models could be easily inter-converted. This will allow system developers to choose a model based on their own preferences. If at a later date a method is chosen for modeling within SNOMED-CT, the data can be converted to conform if necessary.

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I. Introduction

While diagnosis and problem list encoding has been the focus of much research[1,2,3,4,5,6,7,8], physical examination findings have received less attention. Examination findings play an important role in establishing diagnoses and treatment plans. Recording findings in a way that facilitates data retrieval and analysis is important. The long-term goal of this work was to develop a logical means for using SNOMED-CT® for structured recording of examination findings in veterinary medical record systems. Towards this goal, we looked specifically at heart murmur findings, determined by auscultation, in a clinical veterinary setting. Our work proposed two models for structured encoding of auscultatory findings, implemented these models using SNOMED-CT, and then tested each model's ability to store murmur findings taken from clinical records.

II. Background

A. Why look at murmurs?

Cardiac murmurs are important clinical findings. In fact, the nature of a cardiac murmur may provide a presumptive diagnosis and can be pathognomonic for a specific disorder. Often, murmurs suggest the presence of heart disease and prompt further diagnostic evaluation. Further, murmur characteristics are associated with disease severity in some disorders. Therefore, storage of murmur findings in a way that facilitates retrieval and analysis is essential.

Murmur findings in the echocardiographic system[i] of the veterinary teaching hospital at the Virginia-Maryland Regional College of Veterinary Medicine are currently stored as free text in report format. Research has shown that information retrieval by free-text searching is inadequate.[9,10] Estberg et al. found that using word searches in free-text medical records yielded a wide range of search sensitivities and concluded that uniform naming of medical concepts is the best way to improve record retrieval.[11] This was confirmed in a study done by Brown and Sönksen which showed that using a semantic terminological model for encoding medical information significantly improved the mean detection rate for record retrieval when compared to free-text entries.[12] Adequate retrieval and analysis of cases using murmur descriptions requires that these findings be encoded using a semantic model rather than the current free-text entry system.

Structured recording of murmur findings presents several obstacles. The complexity and diversity of murmur descriptions makes it undesirable to attempt to list all possible descriptions within the nomenclature. The process of enumerating and defining concepts within a nomenclature is called precoordination. Concepts that are not precoordinated must be constructed outside of the nomenclature. This is called post-coordination. However, post-coordination requires appropriate attributes which may or may not currently exist for use with murmur concepts. Also the use of range values for attributes in post-coordination has not been addressed. These difficulties are likely to occur with the recording of other examination findings as well.

[i] The echocardiographic system at the Va-Md Regional College of Veterinary Medicine is a Vingmed System FiVe Ultrasound Computer, General Electric Medical Systems, Milwaukee, WI. GE's proprietary software, EchoPac, runs on a Macintosh platform and is used to interface with the ultrasound machine, as well as store, retrieve, and organize data.

The variety of characteristics that can be used to describe murmurs leads to complexity and diversity among murmur descriptions. It is generally accepted that murmurs are described by as many as eight characteristics. These characteristics are: intensity, timing within the cardiac cycle, configuration, duration, pitch, quality, point of maximum intensity and area of radiation.[13,14,15] A veterinarian could use any or all of these characteristics to describe a murmur. Assuming that each characteristic can only be used once, there are two hundred fifty five possible combinations. This number increases dramatically when you account for all possible values for each characteristic and the fact that the sound of the murmur might radiate to more than one location on the chest wall. Since there is no limit to the number of potential points on the chest that can be considered for point of maximum intensity and area of radiation, the possibilities are infinite. Also, veterinarians do not use every characteristic for each murmur description. This may be because it was not possible to appreciate the characteristic during auscultation. Veterinarians may also arbitrarily decide to include only the characteristics which they deem as important to the diagnosis in that patient. The wide range of possibilities for combinations of characteristics and values for murmur description, along with the discretion of the veterinarian, makes pre-coordination of murmur finding concepts undesirable, if not impossible. This leaves post-coordination of these concept to medical records developers. A primary goal for our hear murmur recording system is to provide flexibility while maintaining the standardization that is important for data retrieval and analysis, data sharing, decision support and knowledge discovery.

In order to post-coordinate murmur findings in medical records, appropriate attributes must be available. SNOMED-CT currently provides a well defined set of attributes that apply to most, if not all, disorders. These include finding site, causative agent, associated morphology, severity, etc.[16] For our purposes, disorders can be adequately described using the applicable attributes. In contrast, it seems unlikely that a single universal set of attributes can be applied to examination findings. Many examination findings, such as murmurs, cannot be adequately described using the disorder attributes. Furthermore, special attributes needed to describe murmur findings (intensity, pitch, point of maximum intensity on the chest wall, etc.) do not overlap significantly with attributes needed to describe findings based on other clinical techniques (e.g. abdominal palpation). To develop an adequate recording system for heart murmurs, we must either find a way to use the existing disorder attributes or explore other possibilities for modeling these findings.

Finally, records in our system indicated that range values are often used to describe findings. This is true of murmur findings. It is very common to have murmurs described using phrases such as "Grade I-II/VI" or "heard best between the 3rd and 5th ribs at the costochondral junction". Simply creating new concepts for each range is not a practical solution, as this would lead to an explosion of concepts. So, a mechanism for handling ranges is also required.

B. Why SNOMED CT®?

Our interest in SNOMED was as a common source of concepts that can be used to capture, share and analyze data. SNOMED-CT®[17] is a comprehensive clinical reference terminology.[18] Its lineage can be trace from the Systematized Nomenclature of Disease (SND), progressing through many editions, which added clinical and veterinary content and refined its structure.[19] Currently SNOMED-CT is the only standardized nomenclature which includes veterinary concepts. As such, it has been endorsed by the American Veterinary Medical Association. Furthermore, Wilcke and Hahn have explored the utility of SNOMED in capturing general cardiovascular findings and found that SNOMED accurately represented 90% of their sample[20]. Further testing of the potential use of SNOMED-CT in the veterinary medical record needs to be done. This work will serve as an example of how SNOMED-CT can be adapted for use in recording physical examination findings, in particular those related to cardiac murmurs.

C. Current Status

Many of the elements we required were already included within SNOMED-CT. We found a sub-hierarchy of murmur finding concepts. However, we considered the current list of murmur concepts to be inadequate for our purposes. Some concepts in the sub-hierarchy were organizational concepts that serve to categorize the murmurs by characteristic. One example we found was "Heart murmur categorized by cardiac cycle timing." While these concepts enumerated the possible characteristics used to describe murmurs, we felt it inappropriate to use them directly for post-coordinating murmur descriptions. Other concepts, such as systolic murmur, contained one to two descriptors, in this case systolic. Since most veterinarians use more than one or two descriptors to define any given murmur, we considered these concepts impractical for use in a clinical setting. They could however serve as building blocks for more complex descriptions.

The idea of post-coordination has been implemented in other areas of SNOMED-CT. Based on its definition within the SNOMED-CT User's Guide, we regarded post-coordination as the act of defining new concepts by combining (through appropriate attributes) concepts that already exist in SNOMED.[21] We considered post-coordination of murmurs to be preferred over any expectation that SNOMED-CT should develop pre-coordinated content. Given the many combinations of characteristics and values used to describe murmurs, a combinatorial explosion of pre-coordinated murmur concepts would ensue if the latter approach were taken.

Post-coordination can proceed by using qualifier relationships to add additional meaning to existing concepts. This is done by further specifying existing attributes or by adding new characteristics. Further specification of concepts occurs by choosing a subtype of the value for a defining characteristic. This narrows the definition, creating a more specific post-coordinated concept. Post-coordinated concepts can also be created by adding new characteristics using qualifying relationships.[22] Sanctioned qualifying relationships are added to the nomenclature's relationship tables and marked as qualifying relationships. This guides users and developers in post-coordinating concepts.[23] The specific attribute and value are chosen as needed by the veterinarian recording the information. This allows for structured flexibility.

We used the existing heart murmur concepts, along with the mechanism of post-coordination using qualifier relationships, as the basis for our approach to capturing heart murmur data.

III. Methods

Two logical models were developed to facilitate flexible standardized recording of heart murmur examination results using existing SNOMED-CT concepts and post-coordinated SNOMED-CT concept phrases. A micro-nomenclature[i] was developed to support each model. These micro-nomenclatures were created using the structure of the SNOMED-CT nomenclature and were based on subsets of the July 2003 release of SNOMED-CT[24]. Within these nomenclatures, the murmur sub-hierarchy was reorganized by first removing any unnecessary relationships from the subsets. Then new relationships were created as formal extensions[25] of the subsets to reflect the desired organization. To complete our micro-nomenclatures, additional

[i] For our purposes, a micro-nomenclature is a small subset of SNOMED with additional content to support our models.

content was added in a manner consistent with each model. In addition to content considerations, logical methods were developed to represent the values for cardiac cycle timing as a partonomy and for handling values in the form of ranges. Finally, systems for recording and displaying clinical murmur descriptions were created for each model and used to record one hundred clinical murmurs to confirm and compare functionality of the two models.

A. Information Models

The models created for defining and post-coordinating murmurs use a concept – role – value construct. This is consistent with the modified KRSS description logic used by SNOMED to specify descriptions of concepts with the nomenclature.[18]

In the first (Concept-dependent Attributes) model, a role was assigned for each murmur characteristic. Murmur characteristics were identified within sample data taken from VTH hospital records, among the existing murmur findings of SNOMED-CT and in veterinary cardiology textbooks[13,14,15]. The resulting list was reviewed and accepted by our cardiologist. For each role (e.g. "has cardiac cycle timing"), a specific set of relevant values (e.g, systolic, diastolic, etc.) was identified. Figure 1 is a graphical representation of the model.

The second model was based on SNOMED's current use of "Interprets" and "Has interpretation" to create pre-coordinated definitions for findings.[26] In this model we used the roles "Interprets" and "Has interpretation" and a grouping mechanism for roles[27,28] to represent each pair of murmur characteristics and values. Individual murmur characteristics, in the form of observable entity concepts[i], served as values for the role "Interprets"; while the role "Has interpretation" was filled by qualifier values that characterize each murmur characteristic. For

[i] Observable entities (observables) are concepts which represent things that can be observed or evaluated. For example, serum calcium concentration can be evaluated or measured, so the SNOMED concept "Calcium level" is an observable entity.

example to describe a murmur as systolic, the value for "Interprets" would be cardiac cycle timing, and the value for "Has interpretation" would be systolic. For each observable entity in the model, a specific set of relevant values was identified. Figure 2 is a graphical representation of this model.

B. Nomenclature development

1) Initial Subsets

Subsetting is a formal SNOMED-CT mechanism for identifying a set of elements for use in a specific context, in this case descriptions of heart murmur findings based on auscultation.[i] A subset of concepts and relationships was created as the basis for the micro-nomenclature supporting each model. The subsets encompassed findings related to murmurs, as well as any support concepts (attributes/roles, observable entities, and qualifier values) which might have been needed for post-coordination. Relationships between these concepts were also included in the subsets. For our purposes, murmur findings were compiled by retrieving all descendents of the concept "Heart murmur (finding)". This provided all existing murmur finding concepts, as well as navigational concepts in the murmur sub-hierarchy. Next support concepts were manually selected to complete the subsets. These support concepts included the attribute "Laterality", as well as the qualifier values "Left" and "Right" in the subsets for both micro-nomenclatures. The Interprets/Has interpretation micro-nomenclature also needed the attributes "Interprets" and "Has interpretation", as well as necessary concepts from the Observable entity hierarchy. Finally all ancestors of the heart murmur and support concepts as well as the

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[i] A formal subset is a list of SNOMED Concept Identifiers (SCTIDs). The list is then processed against the full copy of SNOMED-CT to retrieve or use the information. This can be done as needed each time a concept in the subset is used, or the list can be converted into SNOMED-like tables containing all the relevant data.

relationships involved were retrieved to allow for visualization and manipulation of the hierarchy.

2) Hierarchy Reorganization

Initial inspection of the subsets revealed that not all murmur findings in SNOMED-CT were auscultatory findings. Concepts which characterized physical findings, such as murmur intensity, were easily identified as murmur auscultation findings. Concepts which identified pathologic and or physiologic processes in their fully specified names, such as atrial septal defect murmur, were considered murmur diagnoses rather than auscultation findings. Based on this difference, murmur finding concepts were separated into two categories: murmurs characterized by physical findings and murmurs interpreted using pathologic and/or physiologic processes. Certain murmurs could not be easily classified on the basis of their fully specified name. In these cases the separation was made based on the value for the role "Finding site" in each concept's definition. If a cardiac valve was listed as the finding site, the concept was categorized as a murmur interpreted using associated pathological and/or physiological processes. When the concept's finding site listed "cardiac structure", we assumed that the valve referred to the murmur's point of maximum intensity and categorized it as a murmur characterized by physical findings. An organizing concept was created for each category as a child of the root concept "Heart murmur", and the murmur findings were placed in the appropriate place as descendents of these concepts.

In order to reorganize the murmur sub-hierarchy, the set of relationships in each micro-nomenclature was modified to better serve the desired organizational scheme. The hierarchies were manipulated using a purpose-built Visual Basic 6.0 tool. Relationships that were no longer necessary in the new configuration were removed. We then used the extension mechanism[i] provided for by the SNOMED-CT framework to add the new relationships needed to form the new murmur sub-hierarchy.

3) Completing the Micro-Nomenclatures

We completed the micro-nomenclatures by extending each to include qualifier values that enumerated the possible values for each of the murmur characteristics. The version of SNOMED-CT with which we were working contained no qualifier values applicable to murmur description. These values were derived by examining the list of murmur findings in SNOMED-CT, a small sample of case data from the VTH, and manual extraction from veterinary cardiology textbooks.[13-15] These qualifier values were to be used directly with the applicable murmur attribute (role) in the Concept-dependent attributes model and as values for the attribute "Has interpretation" in the Interprets/Has interpretation model. Examples of these included systolic and grade I/VI.

Murmur characteristics, such as cardiac cycle timing and murmur intensity, were also added to each micro-nomenclature. Again these concepts were derived by examining the list of murmur findings in SNOMED-CT, case data from the VTH, and veterinary cardiology textbooks. In the Concept-dependent Attributes nomenclature, murmur characteristics were added as attributes, or roles. In the Interprets/Has interpretation nomenclature, murmur characteristics were added as observable entities to be used as values for the attribute "Interprets".

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[i] The SNOMED-CT framework provides for the creation of extensions to allow for the addition of content for specialized situations. The details for creating extensions can be found in the SNOMED-CT Technical Reference Guide that ships with the nomenclature.

Finally, defining and qualifying relationships were added to each nomenclature. All murmur findings based on description of physical characteristics were defined following the information model for each micro-nomenclature. Qualifying relationships were also added to each micro-nomenclature.

In defining each finding based on physical description, one or more relationship tuples, or rows, were added. These were marked as defining relationships[i]. In the Concept-dependent Attributes nomenclature, one relationship row was created for each murmur characteristic described in the finding's fully specified name. Each row contained the finding concept, a role based on the murmur characteristic and the appropriate value[ii]. For example, to define systolic murmur the relationship tuple created contained the following: systolic murmur (finding concept) – has cardiac cycle timing (role) – systolic (value). With the Interprets/Has interpretation nomenclature, a group of two rows, or tuples, for each murmur characteristic (or observable entity) was created[iii] and marked as defining. Each group contains one row using the role "Interprets" and one row using the role "Has interpretation". The murmur characteristic observable entity concept served as the value for "Interprets", while the appropriate qualifier value served as the value for "Has interpretation". So, a defined systolic murmur produced the following: systolic murmur (concept) – interprets (role) – cardiac cycle timing (value); systolic murmur (concept) – has interpretation (role) – systolic (value).

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[i] In order to mark a relationship tuple as a defining relationship in a SNOMED-CT relationship table, the field "CHARACTERISTICTYPE" is given the value of 0. Qualifying relationships are given a "CHARACTERISTICTYPE" equal to 1.
[ii] In the SNOMED-CT structure, the concept is stored in the field called "CONCEPTID1", the role is stored in "RELATIONSHIPTYPE", and the value is stored in "CONCEPTID2".
[iii] Grouping is achieved in SNOMED-CT relationship tables using the field "RELATIONSHIPGROUP". Relationship tuples which are not grouped with any other tuples are given a value of "0". Relationship tuples which are grouped are given non-0 integer values. Values are assigned sequentially to groups, i.e. group 1, group 2, etc. Each tuple within a group is given the same value.

Similarly, qualifying relationships were added to each micro-nomenclature in order to serve as a guide for post-coordination. In the Concept-dependent Attributes nomenclature, this was done by creating a row for each murmur characteristic and marking it as a qualifying relationship. In these relationship rows, the new murmur specific attributes served as the role, and the parent of all possible values for each attribute served as the value. Table 2 lists the qualifying relationships created in the Concept-dependent Attributes micro-nomenclature. In the Interprets/Has interpretation nomenclature, a group of two rows for each murmur characteristic (or observable entity) was added and marked as qualifying. Each group contained one row using "Interprets" and one row using "Has interpretation" as roles. The murmur characteristic (observable entity) then served as the value for "Interprets", while the parent of all possible values (qualifier value) for each characteristic served as the value for "Has interpretation". Table 3 lists the qualifying relationships created for the Interprets/Has interpretation micro-nomenclature. In both micro-nomenclatures, these relationships were related to the concept "Heart murmur". Since this concept is the root of the murmur sub-hierarchy, the relationships can be transferred logically through inheritance to the other heart murmur concepts.

C. Partonomy of cardiac cycle timing values

Structure-Entity-Part (SEP) triplets, developed by Schulz et al[29], were used to depict the part-whole relationships which exist between the cardiac cycle timing values. Each SEP triplet consisted of 3 concepts: a structure concept, an entity concept, and a part concept. See Figure 3. The structure concept was used to convey all or part of a concept. For example in our partonomy of cardiac cycle timing values, one structure concept was "Cardiac cycle timing". This concept encompassed or subsumed "Entire cardiac cycle" (entity concept for cardiac cycle timing) as well as its parts, “Systolic timing” and “Diastolic timing”. The entity concept was a child of the structure concept and was used to convey the entire or whole concept. Our entity concept for cardiac cycle timing was “Entire cardiac cycle” referred to in this context as “Continuous timing.” Similarly, “Holodiastolic timing” was considered to be synonymous with “Entire diastole” (the entity concept for diastolic timing). Also, holosystolic and pansystolic were treated as synonyms for “Entire systole”, and “Holosystolic timing” was used as the entity concept for systolic timing. The part concept of each SEP triplet was also a child of the structure concept and was used as the parent of all of the parts. “Parts of cardiac cycle timing” served as the parent concept of “Systolic timing” and “Diastolic timing”. In SEP triplets, a part-of relationship exists between the part concept and the entity concept, which inherits to the children of the part concept. So in our partonomy, “Systolic timing” was part-of “Continuous timing”.

Just as the whole cardiac cycle was divided into parts, diastolic and systolic were each split into early, mid and late parts. These were also modeled using SEP triplets. Figure 4 is a graphical representation of the cardiac cycle timing partonomy.

D. Mechanism for accommodating ranges

In our preliminary data, we found that the murmur characteristics intensity, cardiac cycle timing and point of maximum intensity were often described using range values. Since the description logic used by SNOMED-CT does not allow for multiple values for a single attribute, a mechanism for handling ranges was needed in order to describe murmurs. A mechanism similar to that used by Das and Musen in dealing with temporal issues in medical records was created to cope with needed ranges.[30] A new attribute, “Has range delimiter”, was used to indicate the values of the limits of the range. If a range was needed as the value of an attribute, the parent of the concepts that would serve as the range delimiters was used as the value for the attribute. Then tuples consisting of “Has range delimiter” and the range delimiters were role grouped with the original attribute. A graphical representation of this mechanism is found in Figure 5.

E. Storing murmur instances

Once the model-specific nomenclatures were complete, software was created to emulate a small portion of a medical records system. Specifically, the software was dedicated to recording cardiac murmur findings. A database for storing case information and murmur descriptions was created for each model using Microsoft Access 2002. The structure of the tables was identical for both models. The table “Cases” stored an auto-generated primary key identifying each encounter, or case (field name: case_key), the hospital identification number of the patient (field name: hosp_id), and the date of examination (field name: case_date). Descriptions of murmurs found on examination were stored in the table “Murmurs”. This table stored an auto-generated primary key identifying the tuple (field name: key), the concept identification number for the base concept “Heart murmur” (field name: conceptid), the identifying number for the attribute concept (field name: attribute), the concept identification number for the value of the attribute (field name: value), a foreign key from the “Case” table identifying the case involved (field name: case_key), an integer value used to group the murmurs being described (field name: murmurgroup), and an integer value used for role grouping (field name: relationshipgroup). Concept, relationship and description tables from each model’s extension were also included in the databases. These were used to supply the identifying codes for the base concept, attribute and murmur, as well as for populating the interface.

Grouping was used for both murmur identification and grouping of roles. All relationship tuples which applied to a specific murmur were given the same integer value in the murmurgroup field. Within the group of rows for a particular murmur, if two or more relationship tuples needed to be grouped together, then each group of tuples was identified by a number (greater than 0) in the relationshipgroup field. This was the case with each murmur characteristic in the Interprets/Has interpretation model, as well as with laterality and ranges in both models. If a tuple did not need to be grouped with another tuple, then its relationshipgroup was zero (0).

To complete the system, a user interface was created using Microsoft's Visual Basic 6.0 to allow for entry of the murmur data. The same interface was used for both models with slight differences in the queries used to store and display the murmurs. The interface allowed the storage and display of hospital ID, examination date, and one or more murmurs for each case. The ability to enter and display coded diagnoses was also added to facilitate future research.

The programming code on the backside of the interface accessed the database specified at startup in order to display, modify, and enter data into the tables. This code varied with the model, and therefore database, chosen. Interface pick lists for murmur characteristics and values were populated dynamically at run time by accessing the concepts, relationship and description tables in the micro-nomenclatures that were created for each model. This was guided by the qualifying relationships which had been added to the micro-nomenclatures.

We obtained 100 murmurs for entry into the systems from the echocardiograph machine in the Veterinary Teaching Hospital of the Virginia-Maryland Regional College of Veterinary Medicine. First we retrieved a list of cases which included echocardiography exams from January 1, 2004 to February 28, 2004. We then printed the reports for each of these cases. Case reports were sequentially viewed. Beginning with cases dated January 1, 2004, every report with one or more murmur noted was kept until 100 murmur descriptions were obtained. Reports with no murmur cited were discarded. Using the systems created, each of the 100 murmurs, along with identifying case data, was entered into the database for each model.

IV. Results

Based on our two theoretical models, two types of data emerged from this work. First, two nomenclatures, based on formal extension SNOMED-CT subsets, were created to support these models. Second, two sets of data were produced while instantiating clinical murmurs using each of the models.

A. The micro-nomenclatures

1) Concept-dependent Attributes Model

The initial subset selected from SNOMED-CT to serve as the basis for the Concept-dependent Attributes nomenclature contained ninety eight concepts and two hundred fifty six relationships. Re-organization of the murmur sub-hierarchy resulted in the removal of thirteen of these relationships. Thirty nine additional relationships were created to place concepts in the desired positions in the new sub-hierarchy.

Further extension of the initial subset required the addition of one hundred sixty four concepts. Eleven new attributes were added: one for each common murmur characteristic (total of eight), one new attribute for range values, and two concepts that served as ancestors of the murmur attributes placing them in the attribute hierarchy. One hundred forty five concepts were added as qualifier values to serve as the values for the murmur-specific attributes. Eight findings were also added. These new finding concepts were added to reorganize the murmur finding sub-hierarchy. See Table 1 for a comparison of the concepts added for each model. Corresponding hierarchical relationship tuples were also created in order to place each of these new concepts into the appropriate hierarchy.

To complete the nomenclature, murmur finding concepts were defined, and qualifier relationships were added to guide post-coordination. This required the addition of sixty seven defining relationships and twelve qualifying relationships.

2) Interprets/Has interpretation Model

The initial subset serving as the basis for the Interprets/Has interpretation nomenclature contained one hundred four concepts and two hundred sixty two relationships. The same reorganization of the murmur findings sub-hierarchy was performed. As with the Concept-dependent Attributes nomenclature, this meant that thirteen of the relationships in the subset were removed, and that thirty nine new relationships were created.

Full extension of the Interprets/Has interpretation nomenclature also created one hundred sixty four concepts. The same one hundred forty five qualifier values were added. The same eight finding concepts were added as well. However, only one attribute, has inclusive range delimiter, was added. This was the attribute to be used in dealing with range values. The ten remaining concepts were added to the Observable entity hierarchy. These were the eight murmur characteristics and the two ancestors added to provide correct hierarchical location. Table 1 shows the breakdown of semantic type of concepts added to each micro-nomenclature. Again corresponding hierarchical relationships were added to place these concepts in the appropriate hierarchies.

Murmur finding concept definitions and qualifier relationships completed this micro-nomenclature. One hundred thirty six defining relationships were created. Twenty qualifying relationships were created.

B. Instantiation of 100 murmurs

One hundred murmur instances were described using eight murmur characteristics. Three hundred eighty three pairs of murmur characteristics and their values were used to describe the one hundred murmur instances. All one hundred murmur descriptions included murmur intensity and point of maximum intensity. Ninety seven of these also included cardiac cycle timing. A breakdown of the murmur characteristics used to describe the one hundred murmur instances is shown in Table 4.

There were ten instances of the use of range values. Six of these ten instances were used as the value for murmur intensity. Range values were used twice for both point of maximum intensity and cardiac cycle timing.

Using the Concept-dependent Attributes model, it took three hundred eighty three rows in an MS Access table to store the three hundred eighty three characteristic/value pairs. Seven hundred sixty six rows were used to store the characteristic/value pairs based on the Interprets/Has interpretation model. Twenty additional rows stored the ten instances of range values in both models.

V. Discussion

Our goal for this work was to develop a nomenclature system in support of structured recording of cardiac murmur findings using the auscultation characteristics of murmurs which was compatible with medical record systems. We rejected the idea of post-coordinating murmur descriptions using existing murmur concepts. If post-coordinated phrases were to be constructed from existing murmur concepts, then all possible children for each category of murmurs which existed within SNOMED-CT would have to be populated. We did not believe that this could realistically be accomplished given the wide range of possibilities. Predicting all needed concepts would be problematic to say the least. Therefore, we constructed two models for post-coordinating our murmur findings using the base concept "Heart murmur" and qualifier relationships we created to further specify the description. Implementation of these models required the creation of micro-nomenclatures, based on the July 2003 release of SNOMED-CT, through the use of SNOMED's subset and extension mechanisms. The micro-nomenclature development reorganized the heart murmur sub-hierarchy, created appropriate values for point of maximum intensity and area of radiation, constructed a partonomy of cardiac cycle timing values and included a mechanism for coping with range values.

A. Information Models

Formal definitions that exist in SNOMED-CT are used to guide post-coordination. The SNOMED-CT Technical Implementation Guide described the process of post-coordination as starting with the canonical definition of a concept, and then refining defining characteristics and adding qualifiers as needed[31]. Since post-coordination was required to avoid combinatorial explosion of concepts from the many possibilities for clinical murmur descriptions, we needed clear and complete definitions for existing murmur findings. Murmur finding definitions that existed in the July 2003 release of SNOMED-CT were ambiguous and did not allow us to utilize all of the common characteristics of murmurs in use in clinical settings. The definitions for the murmur findings within SNOMED-CT utilized only two attributes, “Interprets” and “Findings site”.

In the definition of each concept, “Interprets” was paired with one of the following: “Diastole”, “Systole”, or “Cardiac function”. Since these terms were not formally defined in our version of SNOMED-CT, we were unable to determine their intended meaning. At first glance, it seemed that this attribute-value pairing may have been describing the part of the cardiac cycle in which the murmur was heard. However, systole and diastole were defined in Dorland’s medical dictionary[32] as contraction and dilatation of the heart respectively. As such we considered them to be aggregate functions composed of things such as muscle contractility, electrical conduction, blood volume and flow, etc. We felt that cardiac cycle timing was only one portion of these aggregate functions. Furthermore, our experience told us that evaluating a murmur only gave us information about the timing involved. It did not necessarily give us information about contractility, conduction or any of the other components of cardiac function. Two patients with identical murmurs could have very different cardiac function. Methods in addition to auscultation are required to fully evaluate cardiac function. Therefore, we asserted that when describing murmurs, a more specific term which solely denoted cardiac cycle timing was more appropriate and would resolve the ambiguity in the terms “Systole” and “Diastole”.

All murmurs were also defined using “Finding site” paired with “Cardiac structure”, “Aortic valve”, “Tricuspid valve”, or “Mitral valve”. The choice of the value paired with “Finding site” was inconsistent. For example, while all murmurs with “aortic” in their name had a finding site of aortic valve, concepts with "pulmonary" in their name had a finding site of cardiac structure, not pulmonic valve. Also, "diastolic tricuspid flow murmur" had a finding site of cardiac structure, while all other concepts with tricuspid in their name had a finding site of tricuspid valve. Because of this inconsistency, we were unable to discern the meaning intended by the use of "Finding site" in the definition of these concepts. According to the definition of "Finding site" in the SNOMED-CT User's Guide, it "specifies the body site affected by a condition."[16] We used this definition to guide our assumption that the use of "Finding site" implies that the valve cited is affected by or is the cause of the murmur. When a veterinarian used the term "mitral murmur", he or she could have been saying that mitral valve dysfunction caused the murmur. In this case, the attribute "Finding site" paired with a value of "Mitral valve" appropriately conveyed the suspected cause of the murmur. On the other hand, he or she could also have been referring, not to cause, but to the fact that the murmur was heard best in the mitral area on the chest wall. Having a point of maximum intensity in a valve area on the chest wall does not guarantee that the murmur is caused by a disorder of that valve. For example, according to Marriot in Bedside Cardiac Diagnosis, "the murmur of aortic regurgitation is *usually* best heard near the 'tricuspid' area"[33]. So, in our previous example, the use of finding site paired with mitral would have inappropriately conveyed cause where none was intended. In order to clearly show the meaning intended by the veterinarian or modeler, an attribute other than finding site was needed to describe the point of maximum intensity.

Most importantly, the existing definitions did not include all of the common characteristics of murmurs. Our list of murmur characteristics included cardiac cycle timing, point of maximum intensity, area of radiation, intensity grade, configuration, quality, pitch and duration. Aside from area of radiation, SNOMED-CT used all of these characteristics in its list of murmur findings. However, none of these characteristics was clearly defined in the formal definitions of these murmur findings. For example, "Cardiac murmur, intensity grade I/VI" was defined by Finding site – Cardiac structure, Interprets – Cardiac function. This concept included the characteristic of intensity grade in its name, but its definition did not include any relationships that defined the grade. For our purposes we needed to create relationships for each of the murmur characteristics comprising a complete description. Therefore we created two information models for defining, and post-coordinating, murmur concepts which allowed us to do so.

The first model, designated the Concept-dependent Attributes model, was a direct pairing of murmur characteristics (as attributes) and their values. Figure 1 is a graphical representation of this model. Attribute concepts were created for each of the murmur characteristics. Relevant qualifier values for each characteristic were also created. Once these additions were made, all characteristics could be accurately represented in murmur definitions or post-coordinated phrases.

The second model, designated the Interprets/Has interpretation model, extrapolated the use of "Interprets" and "Has interpretation" from the definition of other SNOMED-CT findings. In this manner, the veterinarian "Interprets" or evaluates each characteristic of the murmur being described and gives an interpretation as the specific value for each characteristic. Figure 2 is a graphical representation of this model. Observable entity concepts were created for each of the murmur characteristics and used as the value for "Interprets". Relevant qualifier values for each characteristic were also created. Using this model, all characteristics could accurately be represented in murmur definitions or post-coordinated phrases.

In comparing these models, we first looked at the micro-nomenclatures that were created to support each model. In each micro-nomenclature, the total numbers of new concepts added to the original SNOMED-CT subsets were equal. The same concepts were needed as qualifier values in both models, and were added to both micro-nomenclatures. The murmur characteristics were also added to both micro-nomenclatures, but were added to different hierarchies. For the Concept-dependent Attributes model, murmur characteristics were added as attributes. For the Interprets/Has interpretation model, they were added as observable entities.

Difference between the models was seen in the number of relationships (rows) in a relational table, used to define and post-coordinate murmur descriptions. Within the micro-nomenclatures created, definitions of the existing murmur finding concepts required twice as many relationships when using the Interprets/Has interpretation model. This same trend was seen in the tables used to store the 100 murmur instances. Storing the three hundred eighty three characteristic-value pairs took three hundred eighty three rows using the Concept-dependent Attributes model and seven hundred sixty six rows using the Interprets/Has interpretation model. While a two to one difference in storage obviously existed, the significance of this difference was questionable given the relatively inexpensive nature of computer storage space and processor speeds in the current market.

Finally, while the models were inherently different in the way that they handled and stored the information given in murmur descriptions, the fact remains that they both contained the same information and were thus inter-convertible. The attributes in the Concept-dependent attributes model contained the same information as the observable entities in the Interprets/Has interpretation model. Also the values for the attributes in the Concept-dependent Attributes model were the same values found paired with Has interpretation in the Interprets/Has interpretation model. The relationships shown in Figure 6 could be used to guide automation of the inter-conversion between these models. The similarity between the models was further seen in the fact that the database structure and user interface for the systems using both models were identical. So either could be used in a system, and then if necessary a conversion of the data could be made to accommodate outside interactions.

B. Re-organization of heart murmur sub-hierarchy

We concluded that two different types of murmur descriptions could be used in medical records. The first type, physical description, accurately describes the auscultation (physical examination) characteristics of the murmur without attempting to convey the cause or anatomic origin of the murmur. An example of this type is a systolic, grade II/VI murmur heard best (PMI) over the mitral area. This type of murmur description was the subject of this investigation. The second type, cause-based description, specifically conveys the pathologic or physiologic cause or the anatomic origin of the murmur. If a veterinarian feels that a murmur sounds like it is generated by a shunt, the term shunt murmur might be used in the medical record rather than a physical description of the murmur's characteristics. It was our opinion that these two types of murmur descriptions carry different types of information. As such, they are likely to be used in different contexts making it useful to have them exist in separate branches of the SNOMED hierarchy. For example, a medical record designer may only want to allow veterinarians to use murmur findings based on physical characteristics during the recording of the physical exam, but allow them to use the findings which infer cause in the problem list.

The version of SNOMED-CT we utilized contained a mixture of murmur finding concepts which utilized one or more of these types of murmur descriptions. Murmur findings based on physical description included concepts such as "heart murmur, intensity grade I/VI" and "systolic murmur". These concepts were organized by the characteristic being described using organizational concepts such as, "Heart murmur, categorized by intensity". Murmur findings which included cause-based descriptions were scattered throughout the murmur sub-hierarchy. These included concepts that referred to a disorder, such as "atrial septal defect murmur" or "shunt murmur". Also included were concepts that referred to a non-disorder cause of the murmur, such as "systolic flow murmur". Finally, there were murmurs that referred to the causative heart valve, such as "aortic ejection murmur"[i]. Some of these cause-based concepts were children of "Heart murmur". Those that also included physical characteristics in their description were descendents of the concepts which organized the physical description concepts. Figure 7 represents a sample of the murmur sub-hierarchy in the July 2003 release of SNOMED-CT.

Our micro-nomenclatures contained a reorganized heart murmur sub-hierarchy which was based on the two types of murmur descriptions. Murmur findings were grouped under two navigational concepts which were placed as children of "Heart murmur". Murmur concepts which included obvious cause-based descriptions in their names were added as children of "Heart murmur interpreted using pathologic and/or physiologic processes". These included concepts such as "Functional murmur" and "Shunt murmur". Concept names that included heart valve names could have referred to either the name of the valve generating the murmur or points of maximum intensity. Therefore, murmur names that included the names of valves were arbitrarily assigned to one or the other of our new hierarchy branches based on their SNOMED definitions. Murmur concepts that included valve names were added as children of "Heart murmur interpreted using pathologic and/or physiologic processes" only if the valve was the

[i] These concepts are potentially ambiguous, since they could refer to either the valve causing the murmur or the description of its point of maximum intensity. For our purposes, we concluded that they refer to the valve causing the murmur if the valve was cited as the Finding Site in its definition.

Finding Site in the concept definition. When the concept's Finding Site was "cardiac structure", we assumed that the valve referred to the murmur's point of maximum intensity and considered it descriptive (auscultatory) in nature. This assumption, whether accurate or not, was necessary for us to proceed. These concepts were added as children of "Heart murmur characterized by physical findings". Concepts which contained both physical characteristics and cause in their names were placed in the appropriate places as descendents of both navigational concepts. See Figure 8 for a representation of our re-organized heart murmur sub-hierarchy.

It should be noted that reorganization of the murmur sub-hierarchy was not imperative for our work to proceed. Using the subset mechanism, it would have been possible to manually gather only the murmur concepts which used physical descriptions, and not those that used cause-based description. We chose to include and reorganize all of the murmur concepts in our micro-nomenclatures. This allowed us to demonstrate an organizational structure that would depict the semantic difference between the two types of concepts and facilitate the selection of murmur types.

C. Mechanism for coping with range values

Veterinarians often state a range of values for a murmur characteristic. For example, if a murmur varies in intensity, it may be described as a "Grade 1-2/6 murmur". Other examples include "Early to mid systolic murmur" and "Murmur heard best between the 3rd and 5th intercostal space at the costochondral junction". In fact, in the one hundred murmurs that we reviewed, a total of ten range values were used. These were used as values for the characteristics murmur intensity, cardiac cycle timing and point of maximum intensity. This was problematic because the description logic used by SNOMED-CT only allowed for single concepts to serve as the value for an attribute. While we could have create a single concept for every possible range, this would have lead to an undesirable explosion of concepts. Furthermore, it would have been impossible to predict all of the needed ranges, especially for points of maximum intensity and areas of radiation.

In order to allow for the use of range values without having to create new concepts, we proposed a mechanism for coping with range values within the description logic framework of SNOMED-CT. Das and Musen developed a model for handling time stamps and periods of time in medical records. This model converted all time data to ranges. Start time, stop time and the units used were recorded. The units were represented on a continuum with representation for differences in granularity.[14,34] Our mechanism for handling ranges in murmur description was similar. The delimiters of the range in question can be seen as the start and stop points. However, in our work, units and ordinality were either inherent in the concepts used as delimiters and need not have been stated, or they were not applicable to the range at all. For example, in the intensity range "grade I/VI to grade II/VI", ordinality was expressed by the grading scale which was stated in the delimiter concepts themselves. In addition, we considered area of radiation and point of maximum intensity to be spatial areas not points on a scale or mathematical continuum. In this case, the delimiters were borders of an area which were not ordinal and did not require units.

In our mechanism for coping with range values, a new attribute, "Has range delimiter", was used to specify the delimiters or borders of the range value. An object-attribute-value (OAV) triple, using this new attribute, was created for each range delimiter or spatial boundary. The triples were then tied together with the murmur characteristic using role grouping. Since there was no single value to serve as the value for the murmur characteristic, the immediate parent of the range delimiters was used as a placeholder. See Figure 5 for a graphical representation.

This mechanism was applied to both information models. It is important to note however that handling range values in this manner necessitated role grouping for both models. Thus role grouping could not be avoided in the Concept-dependent Attributes model.

D. Values for PMI and Area of Radiation

Values for use with each murmur characteristic were added to both micro-nomenclatures. The SNOMED-CT User's Guide stated that values for SNOMED attributes which did not have a place in another hierarchy are found in the Qualifier value hierarchy.[35] For most of the characteristics, this was the obvious place to add the values needed. However, values for the characteristics point of maximum intensity (PMI) and area of radiation were not as clear cut. Since these values relate to areas on the chest, one might argue that they should have been placed in the Body structures hierarchy. However, there are subtle differences in the information carried by these concepts versus traditional Body structure concepts.

PMI is the area or point on the surface of the chest wall where a murmur is best heard. It can be pinpointed to the exact location using ribs and/or intercostal spaces or localized to a traditional auscultation area, such as mitral, tricuspid, or heart base. Ribs, intercostal spaces and many of the auscultation areas are already located in the Body structures hierarchy within SNOMED-CT. However, defining auscultation areas for PMI, such as mitral, tricuspid and heart base, differs from defining typical body structures. The typical body structure is defined by physical landmarks that clearly demarcate where the structure begins and ends, as well as by the structure itself. For example, a femur is the bone located between the hip and the knee. Auscultation areas do not have reliable physical landmarks that clearly demarcate the area. They are demarcated by the properties of the sound transmission from the heart to the chest wall. Factors such as origin of the murmur, intensity of the murmur, additional pathology in the path of the sound waves and size of the animal, all influence the PMI location. In fact because of this variation, the traditional areas of auscultation overlap. These areas were defined by cardiologists based on the part of the heart from which most sounds in that area are thought to originate. This relies on the experience of cardiologists, and is subject to change with further research. The theoretical derivation of these areas makes them differ from true body structures. Furthermore, even PMI values which are described using ribs or intercostal spaces, rather than traditional auscultation areas, are more than just the designated area on the chest wall. They inherently carry information about the origin of the sound. Unlike true body structures, these parts don't exist in isolation. They are dependent on the act of auscultation, and presence of a murmur. Therefore we concluded that areas of auscultation, including both traditional auscultation areas and locations based on ribs and/or intercostal spaces, were not true Body structure concepts. The Digital Anatomist model differentiates between real and virtual anatomical entities. For example, in the Digital Anatomist, the surface of a lung lobe is a *real* surface. However *virtual* surfaces divide lobes into bronchopulmonary segments[36]. We felt that areas of auscultation were also *virtual* body parts created to facilitate a description of the sound generated by the heart as interpreted by the act of auscultation.

The framework of the July 2003 release of SNOMED-CT did not make reference to virtual body parts, and as such, these areas of auscultation did not have a place in any existing hierarchy. So, until a plan for handling virtual body parts is put in place within the SNOMED-CT framework, we felt that the Qualifier values hierarchy was the most appropriate place for these concepts. Placing auscultation areas in the Qualifier values hierarchy was also logically more consistent with the other murmur characteristic values, making programming logic simpler. It should be noted however that precise fully specified names should be given to clearly note that these concepts are areas of auscultation and not body parts. This is obvious in the case of the traditional auscultation areas, like mitral cardiac auscultation area. Perhaps more importantly, the non-traditional areas should also be explicit in order to avoid confusion with true body parts. For example concepts should be phrased like “Cardiac auscultation area at the 3rd intercostal space”. Ultimately, it may make sense to develop a post-coordination strategy for describing these kinds of “virtual” body parts.

Area of radiation is used to indicate areas on the chest wall to which the sound generated by a murmur extends. PMI is a specialization of area of radiation, as it is the area of radiation which is loudest. As with PMI, the traditional and non-traditional auscultation areas were also used with area of radiation. For example, a murmur description might include the phrase “radiates to the mitral cardiac auscultation area.” However, we also found a mixture of directional concepts as well as additional chest wall locations used as values for area of radiation. Examples of these included “Radiates cranially”, “Radiates to the right side”, and “Radiates to the thoracic inlet”.

As with PMI values, the values to be used with area of radiation were added to the Qualifier values hierarchy. The same cardiac auscultation areas were used for area of radiation. Additionally, directional concepts and other thoracic locations were also added as values for area of radiation. As with the values for other murmur characteristics, these values were based on our data and veterinary cardiology textbooks. Further investigation may reveal more values that also need to be added.

E. Cardiac cycle timing partonomy

The cardiac cycle can be divided into parts, systole and diastole. For the purpose of describing murmurs, systole and diastole can each in turn be divided into parts – early, mid- and late. As such, we identified a part-whole relationship between the cardiac cycle and its parts, as well as between all of systole (holosystolic) and all of diastole (holodiastolic) and their respective parts. Previous authors have described the difficulties of representing and using the various types of part-whole relationships and have proposed mechanisms for dealing with them.[37,38,39,40] Subtle variations in part-whole relationship, especially in medicine, cause variation in transitivity, role propagation and concept specialization. SEP triplets were developed by Schulz, Hahn and Romacker to ensure accurate transitivity and overcome inconsistencies in reasoning that tend to occur with part-whole relationships in medicine.[26,41] SEP triplets are used within SNOMED-CT to emulate the part-whole relationship using hierarchical relationships. In this release of SNOMED-CT, the anatomy hierarchy was the only area where the part-whole relationship was modeled using SEP triplets. However in other areas of medicine, "parts-of" biological functions, procedures, patient's life cycle, and the physical exam could also be described. Our work with the cardiac cycle specifically demonstrated one new area for consideration of the use of the SEP triplet schema. See Figure 6 for the cardiac cycle timing partonomy created.

In order to place the cardiac cycle timing values into an SEP triplet construction, we considered continuous timing to be synonymous with all of the cardiac cycle. Similiarly holosystolic and holodiastolic were considered synonymous with all of systole and all of diastole, respectively. In doing this, reasoning patterns could be correctly applied to the relationships between the cardiac cycle timing values. However, many cardiologists would disagree with our use of continuous timing as the entity concept, or entire cardiac cycle. This is because a murmur can be considered continous as long as it starts in systole and ends after the second heart sound (in diastole). In this case the murmur does not necessarily occur during all of the cardiac cycle. Some or all of both systole and diastole are contained within the continuous timing. Whereas in a true part-whole relationship, all of each part is included in the whole. So, the relationship between continuous timing and systolic and diastolic timings is slightly different than a true part-whole relationship. However, despite the subtle variation in the type of relationship, the SEP construction still resolves the issue of the inconsistency in application of reasoning patterns.

It should be noted that there is some debate over what term accurately describes "all of systole". While cardiologists in the field of human medicine, such as Henry Marriot, consider holosystolic and pansystolic to be synonymous[32], there are veterinary cardiologists who disagree. In Small Animal Cardiovascular Medicine, Kittleson and Kienle defined holosystolic murmurs as ending before S2 and defined pansystolic murmurs as those that may last through S2[42]. Also, the Textbook of Canine and Feline Cardiology included a diagram derived from a 1967 paper by Detwieller and Patteron which distinguished between holosystolic and pansystolic with the latter being longer[43]. For our purposes, we chose to use the term "holosystolic" as a synonym for "all of systole" in our partonomy.

VI. Conclusions

Our work was driven by the importance of the structured recording of examination findings in electronic medical records. Examination findings, such as murmur findings, are the basis for diagnosis and as such are important to veterinarians and researchers alike. Structured recording lays the groundwork for effective data retrieval and analysis. With this in mind our models laid out two ways to record murmur findings in a structured way. Both the Concept-dependent Attributes model and the Interprets/Has interpretation model were capable of structured recording of murmur findings. Both models required the addition of the same number of concepts into the micro-nomenclatures used to implement the models. Also, while twice the storage space was needed to record murmurs using the Interprets/Has interpretation model, this difference is likely to be inconsequential in today's computer market. Perhaps most important is the fact that the data stored using these models can be easily converted between the two models. This ability to interchange models means that system developers can choose to use either model according to their own preference. If one of these models is chosen to be used in modeling murmur findings within the SNOMED-CT nomenclature, existing data could easily be converted to conform. Additional work is needed to demonstrate that the use of these models in recording murmur findings does indeed aid in effective retrieval of data. A closer look at the semantic type of the values for point of maximum intensity and areas of radiation, as well as the type of part-whole relationship that exists within the cardiac cycle timing values, is also needed.

Tables

Table 1: Summary of semantic type of concepts added for each model

	Concept Specific Model	Interprets Model
Attributes	11	1
Findings	8	8
Observable Entities	0	10
Qualifier Values	145	145
Totals	**164**	**164**

Table 2: Qualifier relationships for the Concept-dependent Attributes Model

Concept	Role	Value
Heart murmur	Has cardiac cycle timing	Cardiac cycle timing values
Heart murmur	Has murmur intensity	Murmur intensity values
Heart murmur	Has point of maximum intensity	Cardiac auscultation areas
Heart murmur	Radiates towards	Murmur radiation values
Heart murmur	Has murmur configuration	Murmur configuration values
Heart murmur	Has murmur pitch	Murmur pitch values
Heart murmur	Has murmur duration	Murmur duration values
Heart murmur	Has murmur quality	Murmur quality values

Table 3: Qualifier relationships for the Interprets/Has interpretation Model

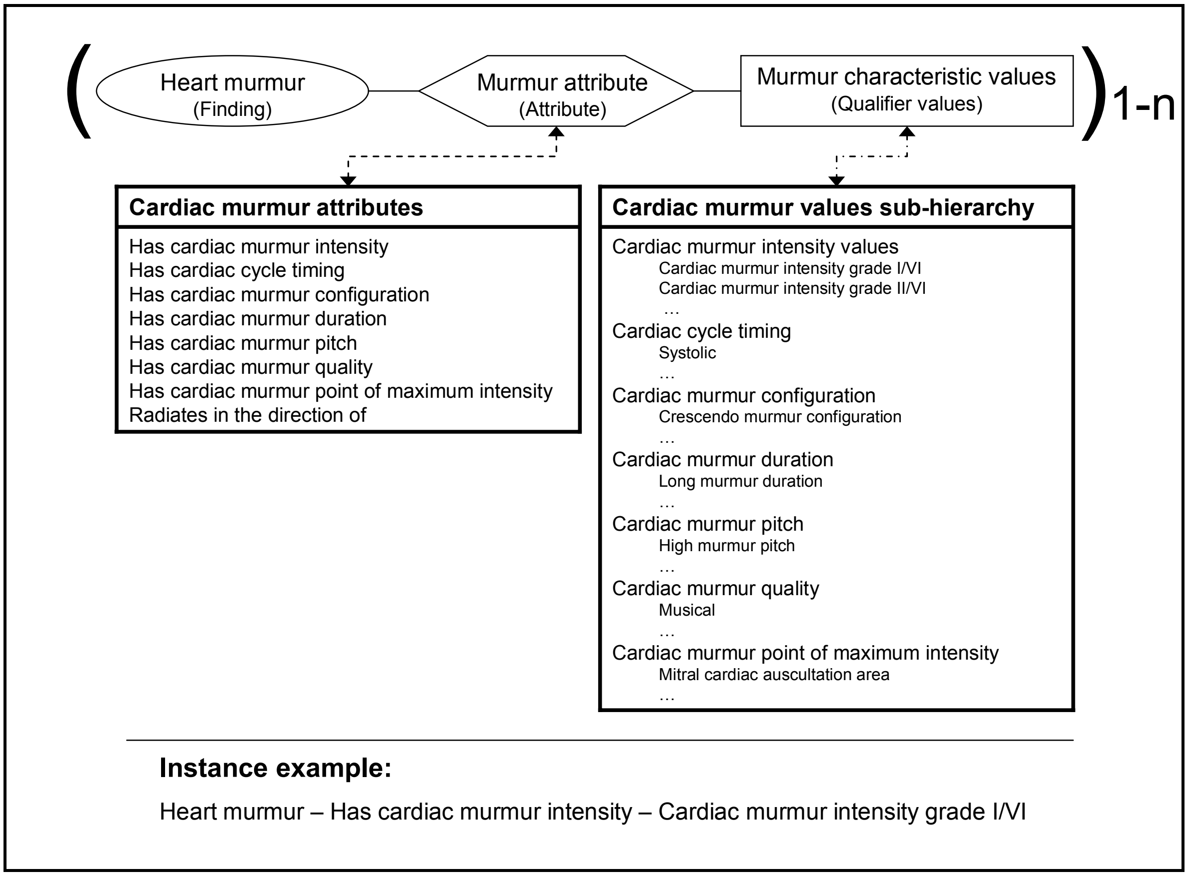
Concept	Role	Value	Role Group
Heart murmur	Interprets	Cardiac cycle timing	1
Heart murmur	Has interpretation	Cardiac cycle timing values	1
Heart murmur	Interprets	Murmur intensity	2
Heart murmur	Has interpretation	Murmur intensity values	2
Heart murmur	Interprets	Point of maximum intensity	3
Heart murmur	Has interpretation	Cardiac auscultation areas	3
Heart murmur	Interprets	Direction of radiation	4
Heart murmur	Has interpretation	Murmur radiation values	4
Heart murmur	Interprets	Murmur configuration	5
Heart murmur	Has interpretation	Murmur configuration values	5
Heart murmur	Interprets	Murmur pitch	6
Heart murmur	Has interpretation	Murmur pitch values	6
Heart murmur	Interprets	Murmur duration	7
Heart murmur	Has interpretation	Murmur duration values	7
Heart murmur	Interprets	Murmur quality	8
Heart murmur	Has interpretation	Murmur quality values	8

Table 4: Breakdown of Murmur Characteristics Used to Describe 100 Murmur Instances

Characteristic	No. of Murmur Descriptions that Use the Characteristic
PMI	100
Intensity	100
Cycle timing	97
Configuration	50
Radiates towards	30
Duration	2
Quality	1
Pitch	1

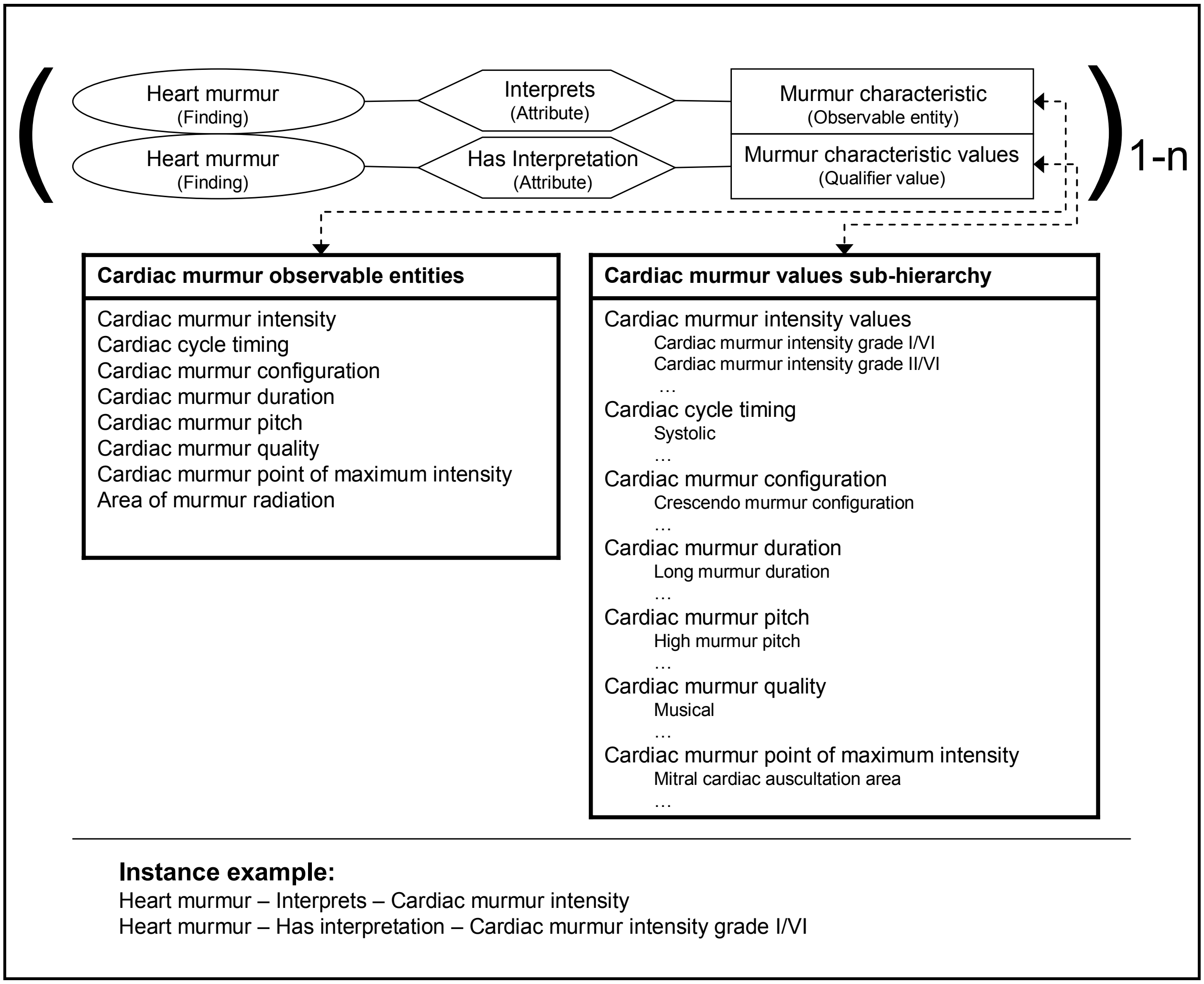
Figures

Figure 1: Concept-dependent Attributes Model Representation.



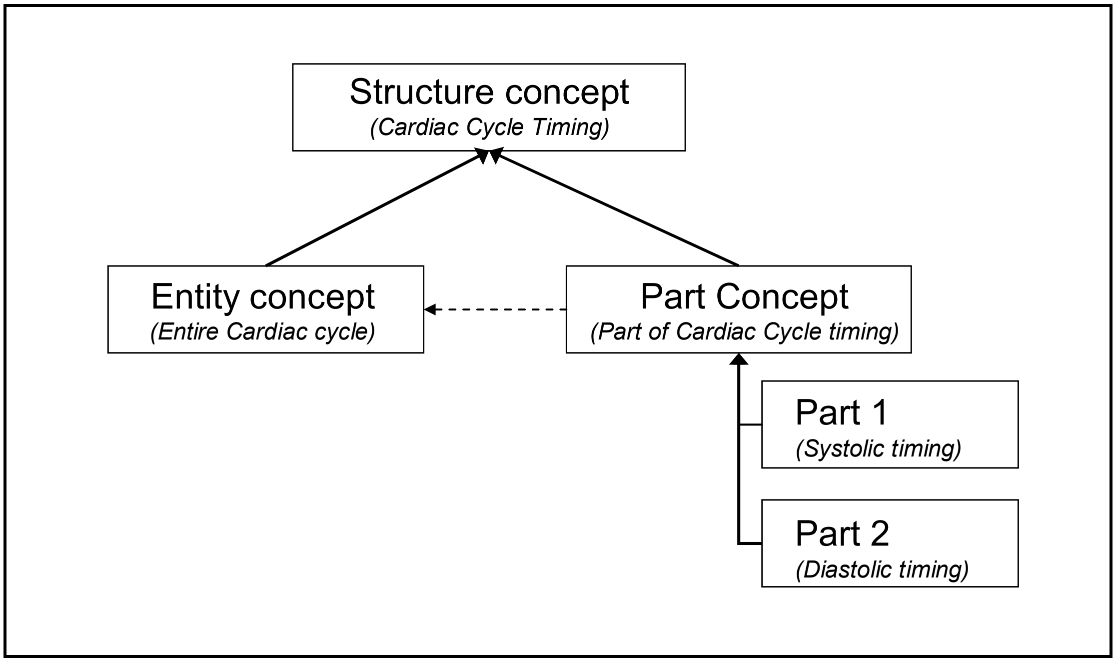
The model uses concept-role-value triples to represent each murmur characteristic. Triples (designated within parentheses) are repeated for each murmur characteristic needing to be described. The finding “Heart murmur” serves as the concept. The cardiac murmur attributes and cardiac murmur values created for use in the model serve as the role and value, respective. In order to represent an instance of a specific characteristic, the appropriate role and value are chosen from the lists of attributes and values created.

Figure 2: Interprets/Has Interpretation Model Representation



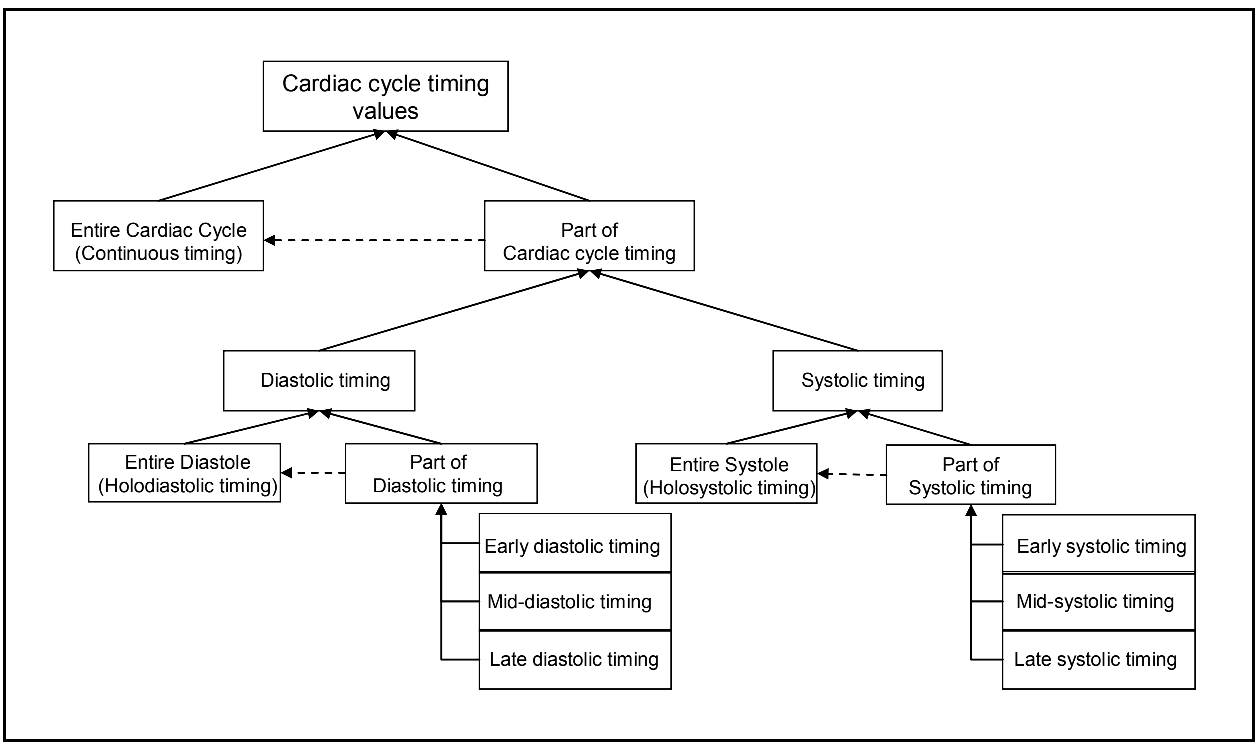
The model uses concept-role-value triples which are grouped to represent each murmur characteristic. Groups of triples (designated within parentheses) are repeated for each characteristic described. The finding "Heart murmur" serves as the concept for each triple. The cardiac murmur characteristics (as observable entities) and cardiac murmur values created for use in the model serve as the values for the roles "Interprets" and "Has interpretation", respectively. In order to represent an instance of a specific characteristic, the appropriate values are chosen from the lists of characteristics and values created.

Figure 3: SEP Triplet Construction



Hierarchical (Is-a) relationships are represented by solid arrows. Part-of relationships are represented by a dashed arrow.

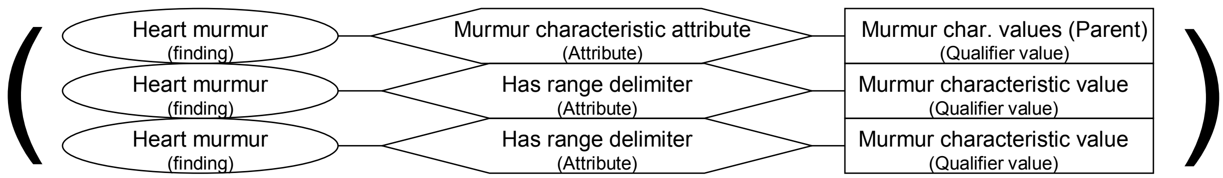
Figure 4: Cardiac Cycle Timing Partonomy



Hierarchical (Is-a) relationships are represented by solid arrows. Part-of relationships are represented by a dashed arrow.

Figure 5: Mechanism for Handling Ranges

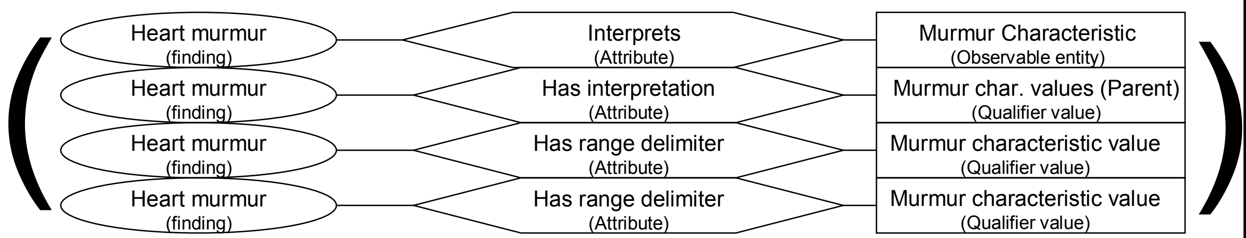
Concept-specific Attribute Model



Instance example:

Heart murmur – Has murmur intensity – Murmur intensity grades
Heart murmur – Has range delimiter – Murmur intensity grade I/VI
Heart murmur – Has range delimiter – Murmur intensity grade II/VI

Interprets/Has interpretation Model

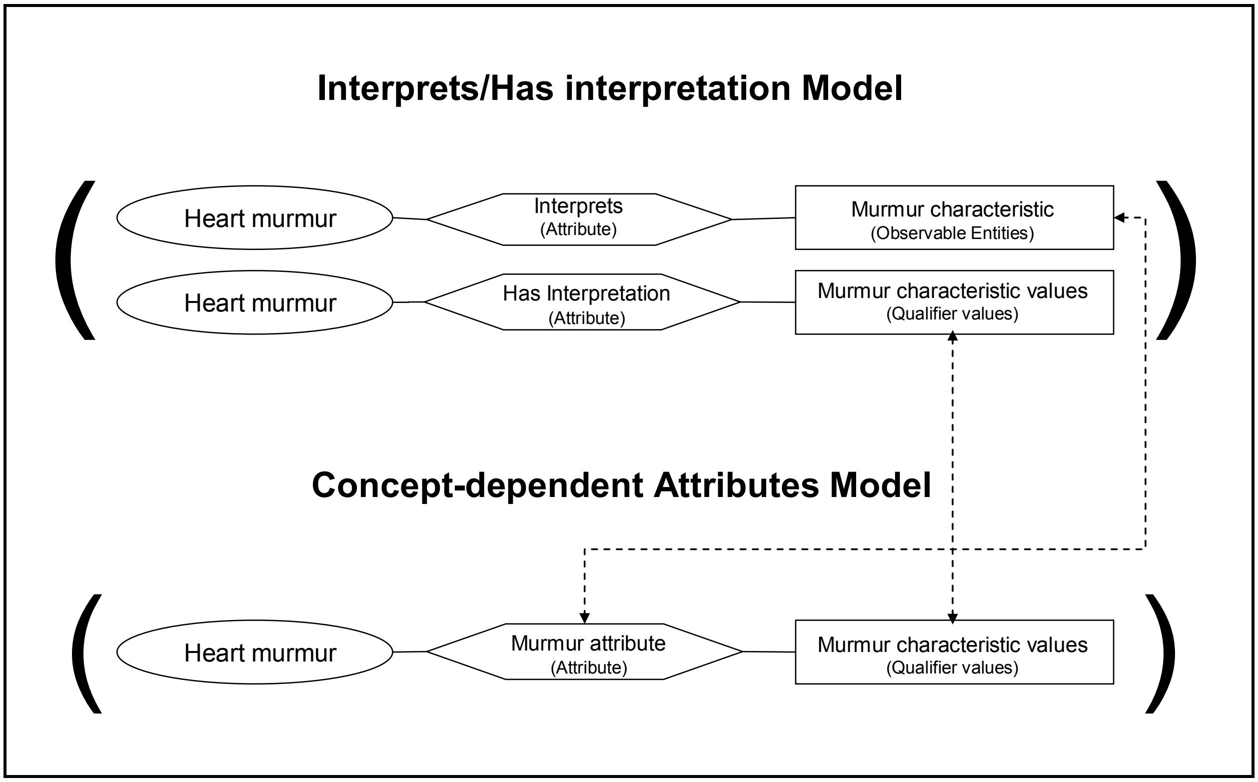


Instance example:

Heart murmur – Interprets – Cardiac murmur intensity
Heart murmur – Has interpretation – Murmur intensity grades
Heart murmur – Has range delimiter – Murmur intensity grade I/VI
Heart murmur – Has range delimiter – Murmur intensity grade II/VI

The model for range values takes the base models and adds triples for each delimiter needed to specify the range or spatial area. All triples are then grouped (designated by parentheses).

Figure 6: Relationship between the models for this study



Concepts containing the same information are connected with dotted lines.

Figure 7: Murmur sub-hierarchy currently in SNOMED-CT

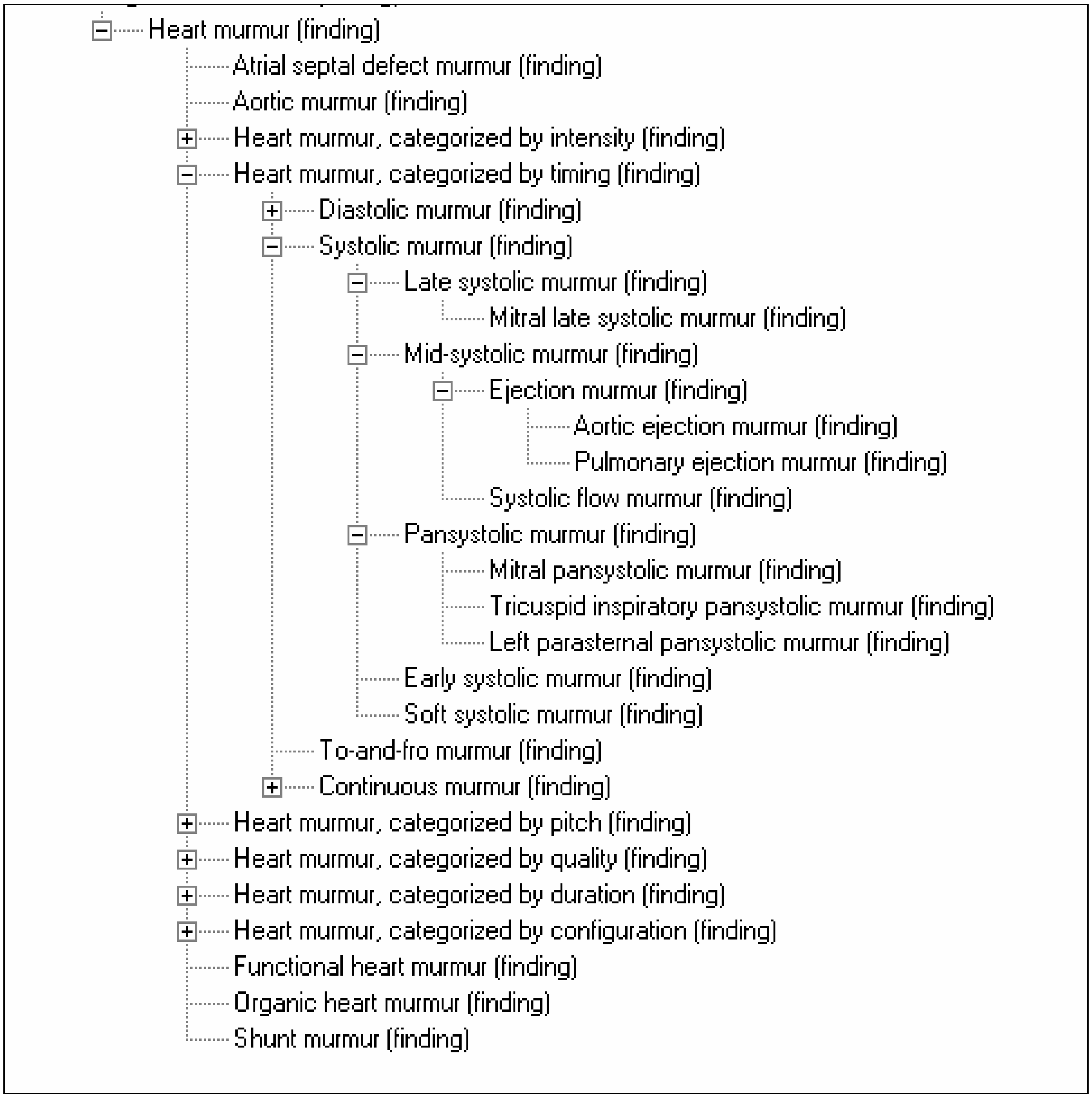
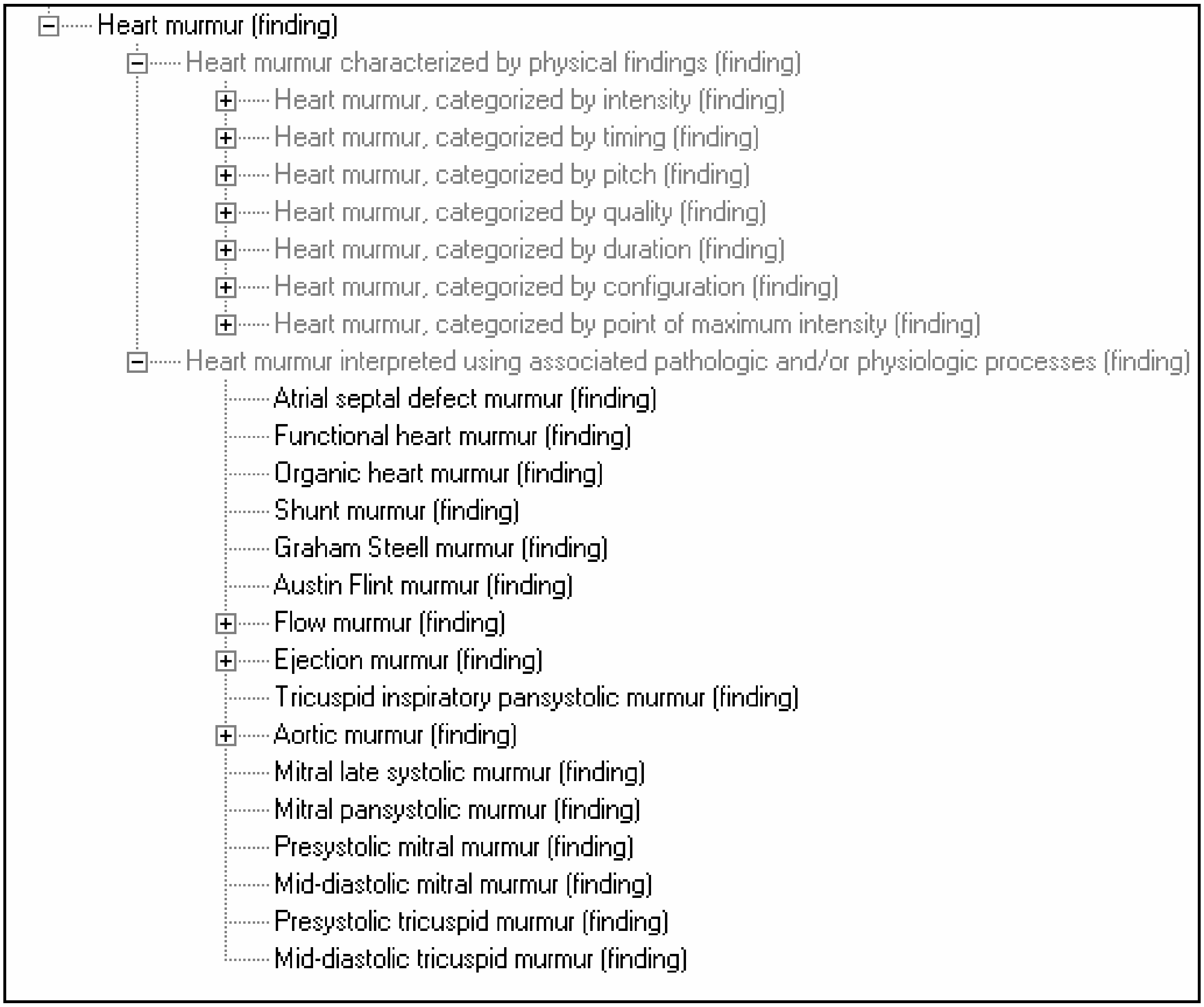


Figure 8: Reorganized heart murmur sub-hierarchy



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