KNOWLEDGE ENGINEERING IN NURSING: Knowledge Engineering Methods for a Pressure Ulcer Expert System for Clinical Nurses

by

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## ABSTRACT

The goal of knowledge engineers is to develop expert systems to help non-experts solve problems ordinarily requiring human expertise. An integral part of knowledge engineering is determining how to help experts articulate their expertise. In spite of decades of research however, there is no well-defined or universally accepted method of knowledge engineering. This thesis has introduced an approach to knowledge engineering for eliciting nursing knowledge. The domain of pressure ulcer prevention and management knowledge was selected, elicited and represented in a conceptual model. The part of the conceptual model representing pressure ulcer prevention knowledge was used as the basis of an implementation model, then incorporated onto VPExpert's™ expert system shell in the form of **IF-THEN** statements.

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# ACRONYMS

| | |
|---|---|
| AI | Artifical Intelligence |
| CANDI | Computer-Aided Nursing Diagnosis and Intervention |
| COMMES | Creighton On-line Multiple Modular Expert System |
| CYBERNURSE | a nursing expert system prototype |
| DENDRAL | Dendritic Algorithm Expert System |
| ES | Expert System |
| ET | Enterostomal Therapy |
| GPS | General Problem Solver |
| GVHS | Greater Victoria Hospital Society |
| JdeFHS | Juan de Fuca Hospital Society |
| KA | Knowledge Acquisition |
| KAF | Knowledge Acquisition Facility |
| KE | Knowledge Engineering |
| LISP | an AI programming language |
| NPUAP | National Pressure Ulcer Advisory Panel |
| VPExpert | a commercial expert system shell |

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# 1. BACKGROUND

## 1.1. Artificial Intelligence

### 1.1.1. What is Artificial Intelligence?

Webster defines intelligence as "the ability to learn or understand from experience; the ability to acquire and retain knowledge; mental ability; the ability to respond quickly and successfully to new situations; the use of the faculty of reason in solving problems, directing conduct, etc., effectively" [1, p.600]. While the words *intelligence* or *intelligent* are frequently used in literature on Artificial Intelligence (AI), definitions are generally not included. To date, there is neither agreement on what the concept of intelligence encompasses nor how it can be measured. The most consistent meaning of intelligence derived from AI literature however, is the human ability to problem-solve by using information as well as applying past experiences to the solution process [2].

Barr and Feigenbaum define artificial intelligence as "the part of computer science concerned with designing intelligent computer systems: that is, systems that exhibit the characteristics associated with intelligence in human behavior — understanding language, learning, reasoning, solving problems, and so on" [3, p. 3]. In other words, AI is concerned with developing computer systems to perform tasks that are presently done by humans and that involve higher mental processes such as perceptual learning, organization of memory and judgmental reasoning [3]. The domains of AI programming currently being developed include:

- cognitive modeling
- expert systems
- natural language processing
- symbolic structure processing
- visual processing
- voice synthesization
- robotics
- pattern recognition [7,8].

Yet few AI systems are ready for widespread use. In fact, the majority of AI systems have not progressed beyond the status of theory and experimentation [4-6].

AI combines hardware and software components in an attempt to emulate human mental and physical processes. These processes include reasoning, decision-making, data storage and retrieval, problem-solving, learning, as well as sensory/motor skills such as hearing, touch and sight. Some AI researchers view artificial intelligence as a branch of engineering as it relates to the construction of intelligent programs such as those used in robotics. Other researchers stress the link with the cognitive sciences where the focus is on the study of human information processing, that branch of cognitive science which uses computers to simulate human reasoning. Still others are interested in the overlap of knowledge, consciousness and AI.

Ultimately, AI is about the emulation of human reasoning — the discovery of techniques that will allow us to design and program machines which emulate our mental capabilities. It is not surprising therefore, that AI should be closely related to a wide range of other academic subjects such as computer science, psychology, philosophy, linguistics and engineering [3]. Although this overlap of disciplines may create friction between researchers due to competing interests, it can be a good source of inspiration and new ideas.

### 1.1.2. History and Development of Artificial Intelligence

Humans have been fascinated by the prospect of intelligent artifacts. With the development of the computer during the Second World War, programmed intelligence became possible. In a 1950 paper, Alan Turing, the founding father of the concepts of AI, asked the question, *Can a Machine Think?* [9]. He argued this new type of intelligence was a legitimate subject, at least for philosophical speculation. As a mathematician and logician, Turing's interests were theoretical while the interests of computer scientists are of an applied nature. Early computer scientists saw that computers could be used to solve problems that were too tedious for humans and they began to speculate whether computers could solve problems that humans could not. This was the inspiration for AI, and in the 1960's, the first AI programs appeared. The first successful AI programs performed tasks previously done by humans such as playing chess and checkers, proving theorems of logic and geometry, solving integrals, and learning concepts [2,3,7].

Reactions to these successes were mixed. Some researchers saw AI programs as the greatest advance that humans had ever made while others wondered whether they were venturing into areas best left to God [6,9]. Researchers believed however, that computers would quickly be developed to tackle problems that previously could only be attempted by the best and brightest minds [2,9,10]. The early successes of AI programs made this goal seem attainable.

A major AI achievement was a program developed by Newell, Shaw and Simon in 1957, called GPS (General Problem Solver). This program could solve puzzles and brain teasers as well prove theorems in predicate calculus. GPS was created to serve as a general or domain-independent problem solver based on general problem-solving techniques such as means-end analysis[1] [7,11]. It was believed the power of GPS could be increased by adding more analysis methods [2,11].

In 1964, Joshua Lederberg created a program to enumerate all possible configurations of a given set of atoms. This program, DENDRAL (DENdritic ALgorithm), was designed to provide chemists with a checklist for chemical compounds needing identification. Through the use of AI, in 1965 Lederberg was able to broaden the program's

[1]Means-end analysis is an important AI technique that compares a current goal with a current task-domain situation to extract a difference between them. This difference is then used to index a function most relevant to reducing this difference [7].

focus to include the identification of molecular compounds from analytical data. DENDRAL became a powerful tool that is still used to solve difficult chemical analysis problems [12,13].

AI had reached a watershed. Many AI researchers sought general, domain-independent methods for problem-solving, while others such as the architects of DENDRAL sought specific, domain-dependent methods. The paradigm-shift in AI was from power-based techniques, which were able to solve different types of problems, to knowledge-based ones which solved problems within clearly defined boundaries. By the late 1960's, DENDRAL was successfully creating hypotheses on the molecular structure of unknown compounds from their mass spectrograms. This direction change from power-based to knowledge-based problem-solving techniques paved the way for the creation of expert systems [12,14].

## 1.2. Expert Systems

### 1.2.1. Definition

It is anticipated that the progressive understanding of human intelligence and reasoning will lead to the development of two products: 1) better models of human cognition; and 2) intelligent artifacts. Expert systems (ES), also referred to as knowledge-based or decision support systems, fall into the latter category and are characterized by a focus on expert knowledge. ES are defined as a class of computer programs that can reach a level of decision-making performance comparable to that of a human expert in a specialized domain that normally requires human specialists or experts to solve [2,15,16]. These problem-solving systems have become one of the most flexible and commercially viable software tools to emerge from AI labs [3].

When expert knowledge can be packaged for a computer it becomes a resource that can be transported and therefore, accessed by large numbers of non-experts. It is the facility to extract and store knowledge that has inspired people to build expert systems. The success of such applications however, is dependent on the selection of a domain appropriate to the limitations of the technology. Domains selected for development should meet the following criteria:

- a human expert must be available;
- non-experts must require the expertise;
- the task must be cognitive;
- the task must not require common sense[2] only;
- the focus of the expertise must be narrow; and
- the time required to complete the task must be under one week [17, p.37].

Examples of domains fitting the development criteria include: deep space station design; chemical synthesis planning; rice disease diagnosis; diagnosis of oil well drilling problems; foundation design for bridges and buildings; weather forecasting; cancer therapy management; and anaesthesia management [7]. Well designed expert systems capture and address a very narrow and well-defined area of human expertise and have proven their use in helping non-experts solve difficult problems [7,11,12,14,18].

### 1.2.2. Expertise and Knowledge Engineering

A human expert is defined as someone who by training, education, experience or insight is able to solve particular problems more efficiently and effectively than others [18]. Experts are adept at applying what they know to problems and tasks, efficient when sorting through irrelevant information when problem-solving and are able to recognize patterns in problems that are similar to problems they have dealt with in the past [20]. While there are no clearly defined criteria for the selection of domain experts, identification may be based on several factors:

- experts may be individuals who by virtue of their status, are expected to be experts;

[2]Common sense knowledge is composed of collected, general knowledge about the world and how it works. It is knowledge that is obvious to most people, such as the judgment of what is right and wrong or the fact that men do not get pregnant. This type of knowledge can in part be taught, but is most commonly collected over time [5].

- experts may be considered expert because of their ability to apply their knowledge to solve particular problems;
- experts may be identified, respected and trusted by non-experts who have consulted them and found their advice or problem-solving to be accurate;
- experts may be identified or highly recommended based on their position of high responsibility and high credibility that could not be maintained if they were not an expert [14,18].

The nature of expertise impacts on the process of knowledge engineering. The goal of knowledge engineers is to develop expert systems that help non-experts solve problems ordinarily requiring human expertise. An integral part of expert system design, or knowledge engineering (KE), is determining how to help experts communicate about 'how they do what they do'. Knowledge engineers must find out from the domain experts not only what they know, but how they apply their knowledge when solving domain problems. One of the greatest challenges for knowledge engineers therefore, is helping experts articulate their knowledge [2,14,16]. To do this, knowledge engineers must develop an understanding of cognitive theories of expert reasoning and their impact on KE in order to produce quality knowledge bases [21,23]. The lack of a general theory of expertise in addition to the lack of any formal KE methodology however, makes this a time-consuming and inexact process.

AI is related to many disciplines such as linguistics, philosophy, engineering, psychology and computer science. A goal common to these disciplines has been the development of a general theory of cognition defining **how** humans reason — a universal theory which continues to be a vigorously pursued subject [19]. Leading researchers in expert system technology have refined this goal to include the development of a cognitive model that emulates how human experts represent knowledge and apply their expertise [5,7,17,19,23].

Research suggests the method that expert say they use in problem solving differs from the experiential knowledge they use in actual problem solving [20,23]. Experts appear to have two distinct types of knowledge: 1) the knowledge they use to explain a problem; and 2) the knowledge they use in actual task performance [13,19-22,24]. Some researchers state that as expertise is gained, experts are no longer able to articulate the reasoning processes involved in the application to their expertise, making knowledge acquisition impossible [13,14,16,24]. Other researchers view **expertise inarticulacy** as more subtle than simple inarticulacy: experts are not always able to explain their rationale using general principles but rather, they are able tell a great deal about what they do in particular cases [20,21]. Researchers in expert system technology conclude that if experts were truly unable to articulate their expertise, knowledge engineers consulting with experts would be a waste of time [21].

Reviews of knowledge engineering literature suggests a wide range and variety of models of expertise[3]. While there is a paucity of research on the nature of expert nursing knowledge, Benner's studies in this area suggest that the Dreyfus' Model of Expertise is consistent with how nursing expertise is acquired [23,24]. This 'Implicit' model defines the acquisition and development of implicit expertise as a progression through five defined levels of skill proficiency: novice, advanced beginner, competent, proficient and expert. Skill progression is characterized by a shift from a reliance on declarative knowledge to an almost complete reliance on intuitive processes [13,23,24]. Benner and Dreyfus suggest that as expertise is acquired, the expert's ability to articulate their expertise becomes lost — the skill has become such a part of the expert that they are no longer consciously aware of deliberate problem-solving or decision-making [8,13,24].

The overall perspective of the Dreyfus' model is that there is a change in the perception of a task environment and mode of behavior that accompanies progressive skill development and acquisition. The progression is

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[3]The existing theories of expertise can be classified under the following five headings: 1) Heuristic; 2) Deep; 3) Implicit; 4) Competence; and 5) Distributed Models of Expertise [23].

> "from the analytic behavior of a detached subject, consciously decomposing his environment into recognizable abstract rules, to involved skilled behavior based on an accumulation of concrete experiences and the unconscious recognition of new situations as similar to whole remembered ones" [13, p.35].

In expert system design, the strengths and weaknesses of any model of expertise shapes the KE strategies and methods the knowledge engineer uses. One characteristic of the Dreyfus' model is that some aspects of expert knowledge are defined as **implicit**, thereby making it difficult to elicit from the domain experts [13,24]. This difficulty is believed to lie within the experts themselves and the process of developing domain expertise [13,22,24]. Understanding the nature of implicit knowledge impacts on what knowledge acquisition strategies the knowledge engineer can effectively employ .

The last decade has seen a growing awareness among leading ES researchers of the potential benefits of modeling human reasoning more closely in expert systems. Expert systems developed using cognitive modeling strategies have several distinct features:

- there is a deliberate attempt to embody within the knowledge base the experts' knowledge as well as the way they acquire and use this knowledge;
- there is an deliberate attempt to incorporate both theoretical and empirical research within the experts' domain; and
- there is a deliberate attempt to employ specific strategies to emulate the cognitive process(es) of the experts that are **not** based solely on the casual observations or intuitions of the system builders [18,19].

The techniques that have the highest likelihood of success in eliciting implicit knowledge and which were used for this research, include: a literature review and protocol analysis [8,13,21,23]. The literature review provides the knowledge engineer with a shallow but broad understanding of the basic vocabulary and concepts of the domain under investigation. A protocol is defined as a record of the expert's step-by-step reasoning and decision-making behavior [8,18]. Protocol analysis refers to a technique where the knowledge engineer acquires the specific and deep problem-solving knowledge from the expert. With reference to clinical nursing, protocol analyses can be conducted using data collected from three sources:

1) verbal descriptions of the expert's domain problem solving;

2) observation of the experts as they apply their expertise in actual problem situations; and

3) written professional nursing standards [13,20,24].

Verbal descriptions of expert decision-making and problem-solving are obtained through extensive interviews with domain experts. Expert observation is a method for acquiring some of the experts' tacit knowledge through direct observation where the expert is asked to 'think aloud' while simultaneously applying their expertise. The knowledge engineer and the expert then meet to refine the domain knowledge from the knowledge engineers' observations and insights. Professional nursing standards are written protocols based on the current state of research findings of a domain area such as pressure ulcer prevention and management. Professional standards are designed as guidelines to assist practitioners in decision-making. These standards are usually developed by independent, multi-disciplinary teams of health care practitioners considered expert in a given domain.

The analyses of the data collected from these sources is expected to aid the knowledge engineer in developing a detailed conceptual model of the domain selected for expert system development.

### 1.2.3. Expert System Components

While ES can include different components and domain knowledge can be structured in a variety of ways, there are certain elements that are common to all: a user interface, a knowledge base, a knowledge acquisition facility and an inference mechanism

[3]. Figure 1 outlines the relationships of the system components, domain expert, knowledge engineer and the user.

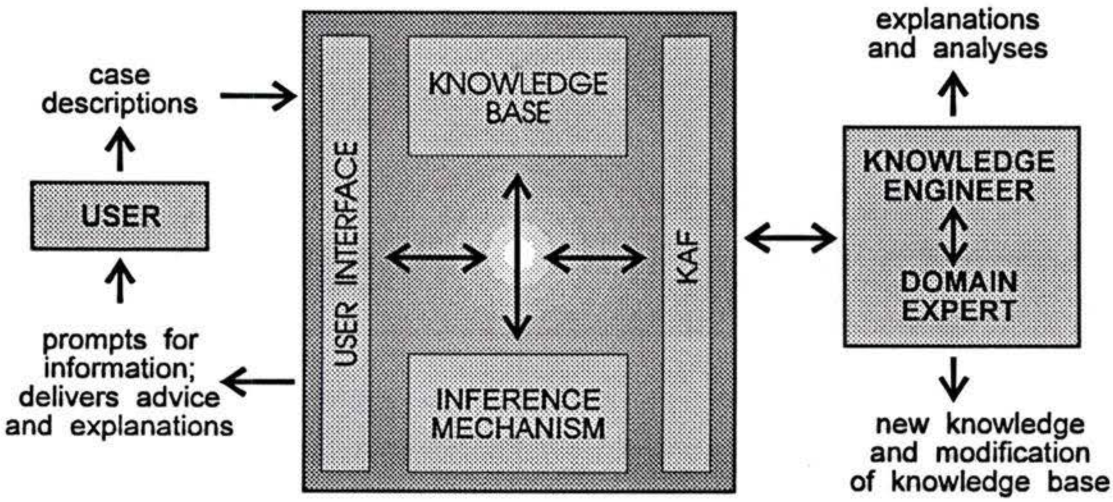


**FIGURE 1 THE RELATIONSHIP BETWEEN THE USER, KNOWLEDGE ENGINEER, DOMAIN EXPERT AND THE EXPERT SYSTEM COMPONENTS**

The user interface is software that provides for the communication exchange between the system user and the expert system [8]. The knowledge-base contains expert-level knowledge on a specific domain. Knowledge stored within a knowledge base is not only what human experts know, but how they use this knowledge to perform their tasks expertly. Knowledge is retrieved from human experts and is stored in a knowledge representational form[4] determined by the inference engine design of the expert system [17,25,26]. This symbolically represented knowledge is then formalized, structured and written into a knowledge base [8,25].

The knowledge base also contains the working memory of the system. The working memory uses knowledge from the knowledge base, combines it with information

[4]Knowledge representation refers to the analysis of expert knowledge, including the facts and rules of thumb used; the determination of how this knowledge should be symbolized in the software of a knowledge-based expert system; and the method used to encode and store the facts and their relationships in a knowledge base [25].

supplied by the user and then uses search strategies (such as backward or forward reasoning) within the inference mechanism to offer advice or arrive at a solution [8].

The knowledge acquisition facility (KAF) is software that provides a mechanism for the dialogue between the system and the human experts for the purpose of acquiring the human expert knowledge. It allows the knowledge engineer to create or modify information in the knowledge base [17,25,26]. The inference mechanism is software that performs the inference reasoning tasks through its programmed search and reasoning strategies. In other words, it is the *thinker* of the system that provides overall control of the decision support system [8,17,25,26].

When expert systems were initially developed, each knowledge base and inference mechanism required programming before the knowledge base contents could be written. As the field evolved, researchers found that it was possible to separate the interpreter (or inference mechanism) from the domain-specific knowledge base. This key design feature is responsible for the commercial success of expert systems. By producing a standard inference mechanism and knowledge bases in a standardized format, it was possible to "unplug one knowledge base and plug in other knowledge bases to the same inference engine, but in different domains of expertise" [27, p.13]. Separation of these two components has paved the way for the creation of a class of interpreters that can be used to construct new expert systems by adding only the knowledge from a new problem domain. The resulting interpreters, termed shells, are how most expert systems are constructed today [7,8].

### 1.2.4. Expert System Engineering

Engineering can be defined as the application of known techniques to new problems [27]. In expert system development, these techniques are those of systems analysis and the design and development of specific systems to meet specific needs. In expert system design however, the knowledge engineer must also deal with a new ingredient termed **knowledge** [27].

Early research in expert system development viewed KE as a process of extracting knowledge 'chunks' from a domain expert [16]. Today, KE is increasingly being viewed as a modeling process where domain knowledge is extracted and then used in the construction of a domain-specific cognitive model [17,19,21,22,23]. The model is then used as the basis for representing the domain knowledge in a knowledge base. The methods used to elicit knowledge are based on the knowledge engineers' understanding and use of cognitive theories of expertise in the KE process.

Understanding the nature of expertise is not just of academic interest, but has significant implications for knowledge engineering. Cognitive scientists construct models of expertise and test them to further scientific understanding of expert cognition. Knowledge engineers use them to define and support the construction of knowledge-based expert systems. The most difficult task facing the knowledge engineer is to help the domain expert structure their knowledge to identify and formalize the domain concepts but by applying a model of expertise that imitates the performance of the expert, the knowledge engineer minimizes the problem of expertise inarticulacy. This is accomplished by the construction of a framework for modeling problem-solving methods and acquiring the expert's knowledge similar to the cognitive problem-solving processes used by the human expert [21,23].

The knowledge engineer must employ one or more techniques to: elicit domain knowledge; interpret this knowledge to make explicit the expert's underlying knowledge and reasoning; and use this interpretation to guide the construction of a model that includes the expert's knowledge and simulates their performance.

### 1.2.5. Expert Systems in Nursing

Much has been written over the last decade about the importance of decision support technology in clinical nursing care. While over 30% of all expert systems developed are aimed at clinical medicine [29], there are few systems in use or under development for clinical nursing [30,31]. In fact, the only widely used system in clinical nursing is the COMMES (Creighton On-line Multiple Modular Expert System), which is presently used at five sites in the US [32]. It is anticipated COMMES will be expanded for use not only to varying clinical sites within the US, but also in international health care facilities [34]. COMMES provides general consultations on the traditional domains of nursing such as general medical-surgical, obstetrical and psychiatric nursing. The learning time and practice needed to use COMMES is estimated to be under two minutes and nurse-users require only a background in nursing vocabulary and patient care problems. [33,34].

Evans describes COMMES as "the largest maintained knowledge base within the health care field in existence today" [34, p111]. The knowledge base contains the equivalent of over 5 million IF-THEN statements and compression techniques allow this huge knowledge base to be contained in a 20 megabyte hard disk [34]. COMMES has reached a stage of maturity extending beyond that of a research prototype only [32-34]. The use of COMMES in clinical environments has fostered the evolution of the knowledge base in response to actual clinical nursing needs [34].

COMMES was developed primarily as an aid to nurses in developing high-quality, patient-specific nursing care plans [33]. A second use of COMMES is to provide nurses with disease-specific information and to suggest possible nursing interventions for each disease process [32,35]. A management information system contained within COMMES allows a nurse-user: 1) to create and store a patient file regarding the care plan protocols; 2) to eliminate patient files upon patient discharge; and 3) to review patient care records for review by quality management teams [34].

Validation studies of the knowledge base suggest COMMES functions at approximately the same level as a Masters-trained nurse [34]. While reports on the impact COMMES has on nursing practice suggest nurses devise more appropriate and thorough patient care plans with, than without, the use of COMMES, little has been reported on the impact COMMES has on patient outcomes [34]. Evans reports that "focused case studies lead us to determine that there are a number of patient outcomes that can be expected as a result of the use of COMMES" [34, p114]. The anticipated benefits include:

- quality care plans leading to greater patient satisfaction;
- quality care leading to fewer patient complications which results in a reduced length of hospital stay; and
- a decrease in time needed to devise patient care plans, resulting in an increase in time nurses can spend in providing patient care [34].

To date, there are no studies confirming realization of these benefits.

COMMES represents a major initiative in the use of expert system technology in nursing. Although innovative, four significant limitations have been identified:

- as a stand alone system, patient information stored within a hospital information system cannot be accessed. All relevant patient data must be entered manually by the nurse-user;
- the highly specific knowledge base must be updated frequently, making it costly and time consuming;
- the user may be required to initiate a lengthy dialogue to obtain obvious information that could also be easily retrieved from standard nursing textbooks or other reference materials; and
- annual maintenance costs are approximately $1 million [31,33,34].

A second example of an expert system developed for nursing is the CYBERNURSE system. CYBERNURSE was developed to the prototype stage and was designed to prompt nurses for patient data, analyze the data and propose a nursing diagnosis and intervention [31,33]. The designers of CYBERNURSE used conceptual models and theories that were intended to represent and model the objects and relationships appropriate to nursing's knowledge base [31]. Development of this expert system was halted for two reasons:

1. the conceptual models were not accurate representations of nursing knowledge; and

2. many of the diagnoses and proposed interventions were obvious to the nurse from the start [31].

A more recent expert system that has also not progressed beyond the prototype stage of development is the CANDI (Computer-Aided Nursing Diagnosis and Intervention) system. Like CYBERNURSE, CANDI was developed to help nurses with the process of nursing diagnosis and is intended for use at the patient's bedside [35]. One factor identified as limiting the adoption of CANDI in a health care organizations is cost. Any hospital organization installing CANDI would require a microcomputer at each bedside [35].

There is a wealth of knowledge and experience embedded in the practices of expert nurses that to date has been inadequately described and shared among the nursing profession. The adequate description of expert practices is essential to the development and extension of nursing theory and practice [21,24,31,33,36]. Systematic description and documentation of expert clinical practice is the first step toward the development and sharing of knowledge and one method of accomplishing this is through the development of nursing knowledge bases.

The development and use of expert systems for decision support in nursing have been few. The greatest development obstacle has been the limitations imposed by the difficulties in defining and representing nursing' knowledge base and by ignorance of the decision-making processes of clinical nurses [33]. The challenge is to represent expert nursing knowledge in a way that is appropriate and accurate and that can be represented in a knowledge base [32,33]. Recent research in ES development suggests that as knowledge engineers apply the KE techniques that have proven successful in other disciplines, these challenges can be overcome [33].

Expert systems are one of the most interesting and potentially one of the most marketable products that have emerged from the AI laboratories [2,16]. While the commercialization of nursing expert systems is still in its infancy, the future will likely see many more expert systems working in new areas on more diverse and complex problems [14,18].

## 1.3. Pressure Ulcers

Health care delivery is a complicated mix of activities, different disciplines and technologies that interact under sometimes very stressful conditions. The challenge that faces all health care professionals is to identify the health care processes that increase the risk of iatrogenic complications and to implement strategies aimed at reducing these risks. Iatrogenic complications have been defined as those inadvertent side-effects and/or complications that occur from the use of acceptable and/or routine diagnostic and therapeutic procedures [36,38]. Pressure ulcers are classified as an iatrogenic complication and are defined as superficial erosions that involve the epidermis and/or dermis layers of the skin or deep ulcers that extend into subcutaneous tissues. These deep lesions may also extend into muscle and/or bone and may be associated with sinus tracts and/or undermining [36,38]. Increases in patient morbidity and mortality rates have been seen for centuries as a direct result of pressure ulcer development [37]. Today, pressure ulcers continue to represent a serious health problem for the individual and an increasing financial burden for the taxpayer.

Improvement in the quality of patient care is a common goal of individual health care facilities and the nursing profession as a whole, yet how this can be achieved is not always clear. One domain where the quality of care can be improved is in pressure ulcer prevention and management. Pressure ulcers are identified as patient care problems where current practice and desired practice are incongruent [39]. While there is a recognized need for continued research related to pressure ulcers, the current level of clinical practice does not reflect the advances in the prevention and treatment of pressure ulcers. There continues to be a time lag or a failure in the implementation of research findings in clinical practice [39,40,45].

Pressure ulcer prevention and management represents a specialized area of practice within the framework of nursing care that requires expertise and also fits the expert system development criteria outlined on page 4:

- nurse-experts in pressure ulcer care and management are available, but they are scarce;
- clinical nurses tend to be domain-novices yet require pressure ulcer expertise in routine practice;
- pressure ulcer prevention and management can be studied and examined as a separate, well-defined domain.

An expert system based on pressure ulcer care and management knowledge is one method of improving the quality of care by making essential information available to non-expert health care professionals consistently and inexpensively [31].

This research includes the definition and formalization of the knowledge patterns and decision-making processes nurse-experts use in the domain of pressure ulcer prevention and management. The resulting expert system is an opportunity to provide novice nurses with a patient-specific pressure ulcer assessment and treatment plan of care based on nurse-expert decision-making. Anticipated benefits of an expert system include:

- assistance for novice nurses in clinical problem-solving resulting in more effective and efficient patient care;

- providing a new avenue for identifying and capturing expert information needed by novice nurses; and

- advancing nursing science and nursing practice by extracting and documenting expert-level clinical knowledge [20].

### 1.3.1. Significance of Pressure Ulcers as a Health Care Problem

Health care organizations are just beginning to recognize pressure ulcers as a costly and partially preventable consequence of care. Effective management of pressure ulcers however, still eludes health care professionals This is due to several factors:

- there is no organizational commitment to determining the extent and costs associated with ulcer development;

- there is no systematic patient risk assessment and intervention;

- pressure ulcer prevention and treatment interventions in early stages of development are rarely initiated;

- appropriate prevention and treatment regimens are inconsistently applied;

- there is poor coordination between nursing, medicine, nutritional and rehabilitative services; and

- appropriate statistics for monitoring and documenting the extent of pressure ulcers are not collected [43,44].

If a pressure ulcer develops and remains untreated or inappropriately treated, it continues to develop, resulting in an increased need for health care. Prevention of pressure ulcers is not complex. A solution to this increasing health and financial problem is: 1) implementing appropriate preventative measures for high risk patients; and 2) accurate assessment of pressure ulcers followed by prompt and appropriate nursing and medical interventions [66].

Researchers in pressure ulcer management have attempted to provide health care professionals with a national standard to guide clinical nursing practice in the consistent application of theory to the care and treatment of pressure ulcers. This continues to be unsuccessful for at least three reasons:

1. a lack of awareness on the part of hospital administrators responsible for implementing clinical care protocols and standards;
2. lack of accurate information disseminated to those health care professionals directly responsible for patient care; and
3. inconsistency of identification and treatment protocols among health care organizations [44,45].

Pressure ulcers have afflicted people for centuries, but the iatrogenic causes of many pressure ulcers can be reduced. Yet it is only those *hands-on* clinical health care professionals who are cognizant of both the causal factors and the interventions constituting appropriate and effective treatments who will be able to reduce the incidence of pressure ulcers [36,40,45].

### 1.3.2. Research Question

Can an expert system be designed as a tool to aid non-expert nurses assess and implement pressure ulcer prevention and management strategies?

The objectives of this project are to create: 1) a model of the knowledge requirements clinical nurse-experts use in the prevention and management of pressure ulcers; and 2) a prototype expert system built using the commercial shell, VP Expert™.

### 1.3.3. Rationale for Research

Public and political attention is now focused on cost-effective and quality health care. To meet this challenge, the US National Pressure Ulcer Advisory Panel is seeking a 50% reduction in the incidence of pressure ulcers by the year 2000 [41]. At an estimated yearly cost of $7.5 billion (US) for treating pressure ulcers, this would result in an annual savings of $3.75 billion [41]. A 1987 report estimates the development of pressure ulcers costs the British National Health Services approximately £420 million annually [46]. Using American incidence statistics[5], numbers and cost-per-day of Canadian acute care hospital beds and the average increase in length of stay for treating a pressure ulcer, one can estimate the annual cost to Canadian health care systems for treating pressure ulcers as ranging from $39.2 to $183.0 million. [See Appendix A]. Assuming a 50% reduction in pressure ulcer development is achievable, this would result in an annual saving of between $19.6 to $91.5 million. Currently however, there is no Canadian national or provincial mandate aimed at reducing the incidence, severity or costs associated with this iatrogenic condition.

Studies dating from the 1960's suggest nurses and their patients can benefit from assistance with decision-making [32]. Research on nursing decision-making illustrates that before making any decision, nurses tend to collect large, idiosyncratic data sets. Factors such as years of experience, age, education, clinical expertise in a particular area and stress levels also influence a nurse's ability to interpret clinical data accurately. These factors frequently lead to errors in clinical judgment [32]. Compounding this problem is that non-expert nurses employ a different decision-making process than that used by expert nurses [13,24]. These findings suggest decision support tools such as expert systems can be successful in improving the accuracy and timeliness of nursing assessments and decisions [32,33].

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[5] With the exception of one 1978 study, there are no Canadian incidence/prevalence statistics collected [47]

Despite differing points of view on the value or appropriateness of expert systems in health care, a well developed expert system has the potential to improve the consistency of care for patients with pressure ulcers [32]. The potential advantage is an increase in patient comfort and a decrease in health care costs [37,48,49]. A well designed expert system that accurately represents expert nursing knowledge can also be used as a tool (where few currently exist) that domain novices can access to advance their own clinical skills.

## 1.4. Summary

There is much debate over whether expert systems can truly be classified as *expert*. It has been argued by others that expert systems do not really operate at an expert-level of performance [9,13]. Human experts are more than mere problem-solvers, they are also proficient at explaining, learning, re-organizing and reformulating while evaluating the progress they are making [13,18,20]. Feigenbaum [16] states there are expert systems performing at the level of human experts in various professional fields, while Schank believes the words *expert system* are loaded with a great deal more implied intelligence than is warranted by their actual level of sophistication [13]. Dreyfus asserts it is highly unlikely that expert systems will ever deliver expert performance and labeling expert systems as *competent systems* would be more appropriate (13).

Regardless of whether an expert system truly mimics human reasoning or performs as well as a human expert, it is still possible to design a program that is capable of clinical decision support [13]. At present, expert systems promise many benefits yet it is unlikely that they will ever completely imitate and/or replace human experts [9]. Expert systems can provide nurses with powerful problem-specific tools that serve as adjuncts to the complicated cognitive tasks associated with decision making. By using tools that can augment their decision-making abilities, nurses are able to select and implement more accurate and timely nursing decisions [23]. The purpose of designing an expert system for pressure ulcer management is to help novice nurses:

- organize and interpret large or unfamiliar amounts clinical data;
- standardize and add consistency to decision-making criteria related to pressure ulcers; and/or
- transfer scarce expertise to remote sites.

A well developed expert system has the potential to improve the consistency of assessment and care of patients with pressure ulcers. The potential advantage is an increase in patient comfort and a decrease in health care costs.

## 1.5. Thesis Outline

Chapter 2 presents the materials and methods used to develop the conceptual model of pressure ulcer activities targeted for knowledge base development. It describes the specific knowledge engineering techniques required to develop and test the concept that an expert system can be developed as a decision support adjunct for non-expert nurses.

Chapter 3 provides a high level conceptual model of pressure ulcer activities and a detailed low level conceptual model of the pressure ulcer criteria and choices related to

1) the assessment process associated with clinical indicators that increase the risk of pressure ulcer formation; and

2) the assessment process associated with the configuration characteristics of a pressure ulcer.

Chapter 4 discusses the development of knowledge engineering methodologies for eliciting nursing knowledge and the constraints associated with expert system use in nursing practice. This chapter also compares current nursing paradigms related to pressure ulcer prevention and management against the conceptual model developed through the use of these KE methods. Limitations and areas of future work regarding this research are also identified.

Chapter 5 discusses the distinction between ES designed for basic versus applied research purposes and concludes with the research findings, strengths and weaknesses associated with this project.

## 2. METHODS AND MATERIALS

Expert system technology is achieving broad acceptance in diverse fields, yet there is no well-defined or universally accepted framework defining the steps of system development. The success of any expert system will depend on how well represented the knowledge elicited from the domain expert is. The knowledge engineer's main task involves designing and employing a knowledge acquisition methodology and then modeling this knowledge in a format suitable for knowledge base development. The generic phases of expert system development include: problem definition; knowledge acquisition; knowledge implementation; and evaluation [12,14].

Expert system design is not a linear function but rather an exploratory and iterative process not yet understood well enough to be optimized by a standard methodology [28]. In fact, in spite of decades of research in expert system development, there remains no universally accepted design methodology [5-8]. The development of any high performance expert system is the result of a gradual and incremental process and Table 1 represents an amalgam of the dominant design methodologies in the area of expert systems. Each design phase description is specific to this research project. This methodology roughly characterizes the process of knowledge engineering that can result in a functional and well-designed program [14,18].

| PHASE | DESCRIPTION |
|---|---|
| Problem Definition | • identify and define scope of the problem; |
| Knowledge Acquisition | • identify and define the key domain concepts and relationships;<br>• create a domain conceptual model; |
| Implementation | • incorporate key concepts of the conceptual model into an implementation model;<br>• create an executable prototype program; |
| Validation | • knowledge base is tested for content validity. |

TABLE 1 AN AMALGAM OF KNOWLEDGE ENGINEERING METHODOLOGIES DEVELOPED FOR EXPERT SYSTEM DESIGN IN NURSING

## 2.1. Research Assumptions

### 2.1.1. Assumptions about Nursing:

Assumption 1. Nurse experts in the area of pressure ulcer prevention and treatment can be identified for this study.

There is no universally agreed upon definition of a **nurse-expert** and there are no definitive criteria the knowledge engineer can use to identify an expert. The knowledge and skills that represent clinical nursing expertise have not been clearly articulated. In fact, identification of nursing experts continues to be based solely on peer recognition [20,32]. For this project however, nurse-experts are defined not only as those nurses acknowledged by their nursing peers as **expert** and who are also presently responsible for the prevention and management of pressure ulcers in their clinical practice.

Assumption 2. Nurse experts in the area of pressure ulcer prevention and treatment are available for this study.

Nurse-experts accumulate knowledge over time and this knowledge is based mainly on personal experience. The expertise of these nurse-experts however, tends to be poorly or inadequately documented and/or communicated to others [20]. To accomplish the task of expert system development therefore, nurse-experts must be available and be willing to make their expertise available to the knowledge engineer.

### 2.1.2. Assumptions about Pressure Ulcers:

Assumption 3: Pressure ulcers are a costly and significant health care problem.

As health care funds diminish, the demand to use health care resources efficiently and effectively increases. There is a lack of quantitative data outlining the costs associated with the care and management of pressure ulcer development in Canadian acute and extended care hospital facilities. Using US costs for treatment and incidence rates however [45], the estimated annual cost to Canadian health care systems may range from $39.2 to $183 million. Given the recommendations of medical and nursing experts that the incidence of pressure ulcers can be reduced by 50%, this could result in a national annual cost savings of $19.6 to $91.5 million (See Appendix A).

Assumption 4. Non-expert nurses require expert knowledge for the effective prevention and treatment of pressure ulcer.

Incidence rates and costs associated with pressure ulcer formation in hospitals as well as research findings suggest that nursing 'inexpertness' is a major factor in pressure ulcer development [44,48,49]. It is assumed that non-expert nurses will perform these prevention and treatment tasks more efficiently and consistently using an expert system that accurately models this domain expertise.

### 2.1.3. Assumptions about Expert Systems:

Assumption 5. It is more cost-effective for a health care institution to buy an expert system than to hire a full-time human expert.

The cost of developing and maintaining an expert human resource is high. The cost of inadequate or inappropriate prevention and treatment interventions is also high. The outcome of a lack of pressure ulcer prevention and treatment nursing-expertise is an increase in patient morbidity which always results in an increased need for medical and nursing care as well as an increase in length of hospital stay [42,45]. Expert systems are tools that have the potential of making expert knowledge permanently available to any health care facility that lacks nurse-experts. The cost of an expert system is less than the costs of hiring a full-time nurse-expert [20]. Given the shortage of nursing experts in pressure ulcer prevention and management and the costs associated with pressure ulcer formation, it is assumed that increasing non-expert access to this nursing-expertise for use in daily clinical practice will help decrease the incidence of pressure ulcer formation, resulting in a decrease in health care costs [42-45].

Assumption 6. Expert systems are adjuncts to clinical decision-making not replacements for human health care professionals.

The purpose of this project is to test the concept that an expert system that can be designed as a decision-making tool for non-expert nurses. The proposed system is not intended as a replacement for human decision-making, but rather as a tool that can be used by non-experts seeking expert advice. The role of the non-expert nurse user includes exercising individual clinical judgment and decision-making even when using an expert system. The role assigned to the expert system is to provide another opinion or advice in this decision-making process. Responsibility for decision-making therefore, always remains with the individual practitioner.

## 2.2. Expert System Development Life Cycle

Decision-making is a complex perceptual-cognitive-affective process. To make a decision, data is collected from the environment (perceptual), the data is interpreted using professional knowledge (cognitive) and then a diagnostic label and/or a set of actions appropriate to the decision situation are selected (affective) [23,32]. To identify and understand a domain's concepts that must be considered in decision-making, the knowledge engineer creates a conceptual model. This model is defined as a limited representation of the domain and requires the identification of the domain's basic elements: concepts; attributes of the concepts; and the relationships between concepts [50,51].

Experts use conceptual models as templates for the organization of their observations and in determining actions [22]. Nurse experts use conceptual models as templates for organizing their clinical observations and determining nursing actions. The knowledge engineer uses a conceptual model as a structured approach in determining the steps necessary for expert system construction.

Each expert system is founded on a unique set of concepts that represents the requirements and consequently, dictates the steps needed for development. One of the knowledge engineer's first steps therefore, is to create a conceptual model representing the expert system life cycle. This conceptual model then, is a structured approach to decision-making that defines the essential steps in designing a pressure ulcer prevention and management expert system. Using the developmental phases of the knowledge engineering process as a guide, Figure 2 represents a generic conceptual framework for any expert system development process. The construction of methods required to accomplish these steps however, is unique to this project's expert system and are outlined in subsequent sections.

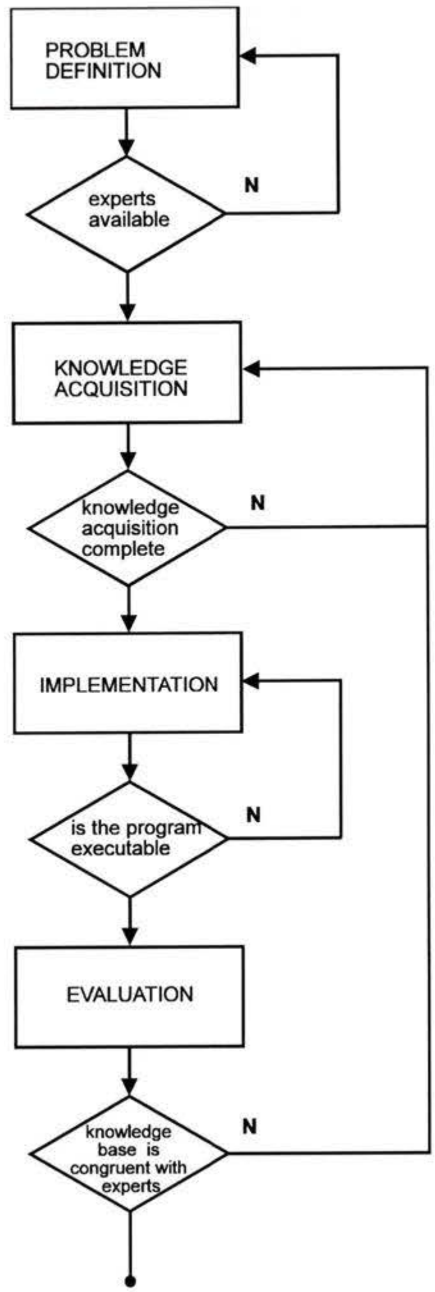


**FIGURE 2 EXPERT SYSTEM LIFE CYCLE**

The process of *Problem Definition* may result in a problem that is suitable for expert system development. Without human experts who can commit the required time for the knowledge base development and evaluation however, the expert system cannot be pursued. Once *Knowledge Acquisition* has been accomplished, the experts are consulted to ensure the conceptual model is an accurate reflection of the decision-making process used by the experts. When an *Implementation* model has been successfully executed, the knowledge base contents are *Evaluated* to determine the congruency between the system output and the expert's advice.

### 2.2.1. Problem Definition

The purpose of this phase is to determine whether an expert system could be designed as a decision-support tool for use by non-expert nurses in the area of pressure ulcer prevention and management. Problem Definition consists of two distinct steps: Step 1) identify objectives; and Step 2) collect data that will enable the author to meet these objectives.

**Step 1:**

OBJECTIVE 1) identify and define the scope of the problem area the expert system would address;

OBJECTIVE 2) identify all key players required for the development and testing of the system; and

OBJECTIVE 3) define the goal and objective of the expert system [7,18,28].

**Step 2:**

Domain-specific information was required to address these objectives. Questions were constructed that when answered, would generate the data necessary to enable the author to fulfill the identified objectives. These questions included:

1) How suitable is the domain of pressure ulcer prevention and management for expert system application?
2) Are nurse experts available for the development of the knowledge base?
3) What errors do novice practitioners typically make that experts do not?
4) How will an expert system reduce these errors?

Following the construction of these key questions, clearly outlined tasks and strategies were then devised in order to collect the data necessary in answering these questions. While these strategies (outlined in Tables 2, 3, and 4) suggest a linear approach to data gathering and analysis, the process is in fact, iterative.

| |
|---|
| **OBJECTIVE:**<br><br>identify and define scope of domain |
| **TASK:**<br><br>literature review |
| **STRATEGY:**<br><br>• University of Victoria library search of relevant information;<br>• GVHS Medical library search of relevant information;<br>• obtain standards written by professional bodies i.e.) National Pressure Ulcer Advisory Council and the International Association of Enterostomal Therapists. |

**TABLE 2 OBJECTIVE, TASK AND STRATEGIES USED TO IDENTIFY AND DEFINE THE SCOPE OF THE SELECTED DOMAIN**

Examining the results of research on pressure ulcers through textbooks, medical and nursing journals was essential in identifying the terminology and basic concepts associated with pressure ulcer prevention and management. This allowed the author to develop the domain vocabulary necessary to communicate effectively with the nurse-experts. The data collected from fulfillment of the strategies listed in Table 2 enabled the author, in conjunction with the nurse-experts, to answer questions 1 and 3 (listed on page 30.)

| |
|---|
| **OBJECTIVE:**<br><br>identify all key players needed for the development, implementation and testing of the expert system |
| **TASK:**<br><br>identify and determine availability of nurse-experts |
| **STRATEGY:**<br>• obtain nurse-expert advice on seminal works and key domain authors;<br>• contact vice president of patient care (GVHS) to determine existence and location of expert-nurses;<br>• contact nurse manager in charge of domain expert nurses;<br>• obtain permission to approach nurses by explaining purpose and goal of research;<br>• approach faculty in the University School of Nursing to determine interest and availability of expert-faculty to act as consultant for knowledge base development;<br>• arrange interviews with the nurse-experts to determine whether pressure ulcer assessment and management is a nursing problem;<br>• consult with nurse expert(s) to determine the types of clinical errors novice-nurses make related to pressure ulcer prevention and management. |

**TABLE 3 OBJECTIVE, TASK AND STRATEGIES USED TO IDENTIFY THE KEY PLAYERS REQUIRED FOR EXPERT SYSTEM DEVELOPMENT**

Identification of the key players required for the expert system development was a two-part task: 1) identify the nurse-experts and 2) obtain a commitment from them to be available for the duration of the project. An initial investigation led to the identification of skin care nurse-experts employed by the GVHS and the Juan de Fuca Hospital Society (JdeFHS). GVHS nursing administrators (Ms. Coward[6] and Ms. Gloster[7]) granted permission to approach these nurse-experts and informed these nurses they would be contacted by the author and the JdeFHS clinical nurse specialist (Ms. J. Mantle) was also

[6]Ms. Coward is Vice-President of Patient Care for GVHS.
[7]Ms. Gloster is Nurse-Manager for the Enterostomal Therapy Department.

able to act as a knowledge base consultant. Application of the strategies outlined in Table 3 provided data instrumental in to answering questions 1 through 3.

| |
|---|
| **OBJECTIVE:**<br>determine the goals and objectives of the expert system |
| **TASK:**<br>establish an information collection schedule |
| **STRATEGY:**<br>• review effective communication techniques for knowledge elicitation;<br>• plan goals and objectives for each knowledge engineer-expert interaction;<br>• inform each nurse-expert of time requirements; i.e.) minimum of 12 hours each for interviewing and reviewing domain knowledge;<br>• obtain permission to observe GVHS nurse-experts as they apply their expertise;<br>• arrange first meeting time and place with each expert for the purpose of Knowledge Acquisition. |

**TABLE 4 OBJECTIVE, TASK AND STRATEGIES USED TO DETERMINE THE GOALS AND OBJECTIVES OF THE EXPERT SYSTEM**

Defining the goals and objectives of this project was crucial to designing an expert system that reflected the requirement specifications identified by the nurse-experts. Establishing and maintaining an information collection schedule therefore, was essential. This required effective and ongoing communication between the knowledge engineer and the nurse-experts through the strategies outlined in Table 4. The author and nurse-experts were able to formulate answers to questions 3 and 4, (listed on page 30.). As the goals and objectives of the proposed expert system were defined, a high-level[8] conceptual model of

[8]This high-level model outlines only the most general concepts and decision paths associated with this domain.

pressure ulcer prevention and management emerged enabling the author to progress to the Knowledge Acquisition phase.

### 2.2.3. Knowledge Acquisition

Previous research findings suggested expert-level knowledge is best elicited through the use of literature reviews and protocol analyses [13,24]. The use of multi-method approaches to knowledge elicitation is time consuming but yielded the theoretical and experiential knowledge of the nurse-experts. Throughout this development phase, the knowledge engineer and nurse-experts clarified the key concepts, relationships and information-flow characteristics of pressure ulcer prevention and management. The product was a low-level[9] conceptual model of pressure ulcer prevention and management activities used as a basis for creation of the expert system knowledge base.

#### 2.2.3.1. Literature Review

To understand the nurse-experts in interactions, the author's first step was to collect and study available information of the domain under investigation. The objective of the literature review is to identify the domain terminology and basic concepts. For this project, this background knowledge was gained by studying relevant professional nursing and medical journals and textbooks. Preliminary consultation with a nurse-expert ensured the knowledge engineer was able to identify and study the seminal works related to pressure ulcers.

The initial literature search conducted was shallow and performed to give the knowledge engineer a broad understanding of the domain under investigation. As the knowledge acquisition activities progressed, the knowledge engineer developed a more comprehensive knowledge and understanding of the domain and the current nursing paradigms of pressure ulcer prevention and management. This acquired information was

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[9]This low-level conceptual model highlights the detailed concepts and decision paths associated with this domain.

then used as a guide in formulating knowledge-elicitation questions asked of the nurse-experts in subsequent interviews.

#### 2.2.3.2. Nursing Protocol Analyses

The objective of the protocol analysis is to gain the detailed theoretical and experiential domain knowledge of the nurse-expert that accurately reflects their years of training and expertise. The protocols used for this project were 1) interviewing the experts to get a verbal record of their expertise; 2) observation of the expert as they apply their expertise in actual problem situations; and 3) the written professional nursing standards of care available to expert and non-expert nurses. Information collected by these means was useful in guiding subsequent lines of questioning and as a means of identifying inconsistencies between the expert's verbal description of decision-making and actual observed task performance.

##### Nurse-Expert Interviewing

The major source of information gathered during protocol analyses were personal interviews between the knowledge engineer and the nurse-expert. This method also required the most time and planning to successfully elicit the nurse's experiential knowledge. Prior to each information gathering session, a plan was developed to elicit specific information. Each interview session incorporated the following:

1) identifying and sharing of specific and precise data gathering objectives for each session. This involved:
    - preparedness on the part of the knowledge engineer
    - recording, summarizing and clarifying of collected data with the nurse-experts;

2) the deliberate use of effective communication techniques to elicit knowledge from the experts such as;
    - clarifying, qualifying and feedback techniques;

- attending; and support;

3) developing strategies for identifying and avoiding common knowledge acquisition pitfalls such as:

    - the expert may provide inaccurate information;
    - the knowledge engineer may misunderstand the information;
    - the knowledge engineer may introduce bias during the interview sessions;
    - the experts explanations may wander from the domain under examination;
    - interruptions that may disrupt the interview sessions [52].

Interview dates and times were arranged and agreed upon by the author and the experts. The purpose and expectations of each person were made explicit at the onset of each interview. Clarity of purpose enabled the knowledge engineer to keep the interview focused on the domain concepts discussed. This preparation ensured the interviews did not overrun or deviate from the knowledge engineering objectives. At the end of each interview, subsequent interview session objectives were discussed and when possible, a date set for the next interview.

The purpose of maintaining a written record was to enable the author and the nurse-experts to conduct post-interview examinations of the knowledge presumed to be reflected in the domain problem-solving. The summarized and clarified information was then used to guide the direction of subsequent interview sessions.

Ultimately, knowledge acquisition is about effective communication between the knowledge engineer and the domain expert(s). The author therefore, deliberately employed specific communication strategies throughout every interviewing session included:

◆ Clarifying, Qualifying and Feedback Techniques such as direct and indirect questioning, summarizing and paraphrasing. Direct questioning imposes a specific direction on the expert. For example, direct questions put to the nurse-expert were phrased as "If a patient presents with a pressure ulcer on the coccyx and is incontinent, what nursing actions would you implement?" Indirect questioning invites the expert to explore a topic and gives them the responsibility for the direction of the interaction. An example of this type of questioning used on the nurse-experts was "Describe for me how you assess whether a patient is at high risk for pressure ulcer development?"

As these techniques were applied and questions such as the above were answered, domain concepts were identified, allowing the author to determine and resolve any inconsistencies and misunderstandings. For example, when concepts and relationships were summarized back to the nurse-experts verbally and using diagrams and the blackboard, direct feedback was also sought from the expert to ensure that the model displayed accurately represented the nurse-expert's domain knowledge and/or thought processes.

◆ Attending and Support techniques where te knowledge engineer focuses attention on what is being communicated verbally and non-verbally by the expert. The knowledge engineer attends to the experts complete message without prejudging or disrupting the meaning or flow of the communication. Attending is useful when trying to establish the limits of the experts knowledge and when trying to establish congruency between literature sources and the expert's application of their expertise. For example, when the nurse-expert was asked whether the concepts identified in the wound Appearance diagram were complete, the response was stated in the affirmative, yet the facial expression was a frown. These types of incongruent cues were used as indicators to probe deeper into the concepts and relationships under discussion.

Support refers to those conscious actions and words used to create a climate of acceptance and freedom to speak. For example, non-verbal behaviors such as facial expression, body posture and tone of voice must be congruent with verbal behaviors. Supportive mechanisms such as genuineness, warmth and respect are intended to demonstrate the knowledge engineer's commitment to gaining an understanding the expert's domain expertise.

In anticipation of potential pitfalls, strategies were also built into the interview process to minimize or avoid these pitfalls. For example, to avoid the problem of inaccurate information for this project, three methods were used: 1) feedback loops were built into the life cycle process to ensure that each phase was revisited and clarified to be accurate; 2) multiple experts were sought and employed throughout the KE process to validate all domain concepts, relationships and nursing interventions; and 3) the research articles and texts were compared to the information gathered from nurse-experts to determine consistencies and/or inconsistencies.

How a knowledge engineer poses a question is the most likely source of introducing bias into the KE process [52]. Another source of potential bias is experts who are flattered at the recognition of their expertise and therefore, try to please the knowledge engineer by telling them what they think the engineer wants to hear. The expert may also feel uncomfortable when they are unable or have difficulty verbalizing their expertise. The knowledge engineer who consistently focuses on **what** the expert does rather than on what the expert **might** do can minimize bias. For this project, questions phrased as follows maintained a focus directly on what the nurse-expert specifically did:

- "Can you remember the last patient you had that presented with a pressure ulcer?;
- "How did you treat this patient?";
- "How did you decide what intervention s/he required?";
- "What treatments would you implement if a patient was a quadriplegic and the nursing unit had no access to recliner chairs?";
- "What does this cluster of clinical indicators tell you?";

Experts may avoid answering immediate questions and instead cover a wider range of information that may not be germane to the domain or reasoning process being developed. Short discussions of other topics can be used to relax the expert and engineer. For example, as the knowledge engineer is usually a stranger to the experts, the first few minutes of an interview session can be spent on social conversation to help each person relax and feel comfortable. While wandering may sometimes be helpful in building a broad picture of the expertise, the knowledge engineer must be prepared to gently refocus the discussion. Balancing the need to focus on the acquisition of domain information and the need for wandering falls to the knowledge engineer.

The purpose of any interview session is to get the expert talking. When the nurse-experts is interrupted during knowledge acquisition, the flow of ideas and information may be disrupted. This can result in a concept being inadequately or incompletely explored, increasing the time the nurse-experts are needed. As the nurse-experts were already working full-time in addition to acting as expert consultants, it was essential to avoid knowledge acquisition delays by preventing disruptions to the flow of information.

To avoid other interruptions, interview sessions are best held in quiet, comfortable settings. Ideally, the expert is able to devote blocks of time scheduled close together to maintain momentum. If interview sessions are held far apart, the progress in obtaining information can be very slow. The knowledge engineer must try and schedule meetings when the expert's attention can be devoted to the task of knowledge acquisition only.

How expert knowledge is manifested and when it is used is what the knowledge engineer must capture and encapsulate in the expert system. While using effective communication techniques may seem obvious, it is critical the knowledge engineer plan for how and when they will be used. A knowledge engineer unable to establish a strong rapport with the experts is unlikely to develop an effective expert system [27].

### Observation

Observation is a method of supplementing information gathered by the literature reviews and nurse-expert interviews. The knowledge engineer observes the performance of the nurse-expert and asks them to 'think aloud' as they complete their tasks. Observation has the advantage occurring in the normal environment of the expert, thus providing cues to the nurse-expert's memory. The knowledge engineer can identify and then discuss aspects of pressure ulcer prevention and management that are consistent and/or inconsistent with the evolving domain conceptual framework.

Permission was obtained from Ms. A. Gloster (Nurse Manager-GVHS) for the author to accompany those nurses responsible for pressure ulcer management as they treated pressure ulcer patients. Permission was also obtained to observe the nurse-expert at the Juan de Fuca Hospital Foundation's Hiscock care facility.

This structured approach to knowledge acquisition increased the author's ability to elicit the heuristic rules and professional experiences of the nurse-experts [12,18]. The subsequent data analysis enabled the author to create a low level conceptual model represented by a critical decision path schema. The purpose of this model was to provide a structure for: 1) defining and organizing the expert's rules and experiences and 2) representing the actual decision-making processes of the experts. This model was then used as the basis for creating an implementation model.

### Examination of Nursing Standards of Care

The professional nursing standards of patient care documents used in Knowledge Acquisition were an aid for the author in translating and comparing pressure ulcer research information with clinical applications. The standards identified by the nurse-experts as seminal research works used in pressure ulcer prevention and management included:

1) the Norton Scale for predicting risk of pressure ulcer formation [55];

2) the Braden Scale for Predicting Pressure Ulcers [56];

3) The International Association of Enterostomal Therapy (IAET) Standards of Care on Dermal Wounds [54]; and

4) National Pressure Ulcer Advisory Panel (NPUAP) Staging Criteria for Pressure Ulcer [66].

The Norton and Braden Scales are risk assessment tools used to predict the likelihood of a patient developing a pressure ulcer. The Norton Scale, developed in the early 1960's, was the first risk profile and was used as the prototype for all subsequent models [55,65]. The non-expert nurse could conduct a rapid patient assessment resulting in a numerical score that indicated the severity of the risk for pressure ulcer development. While researchers believed the Norton Scale was a reliable and practical clinical tool, small scale studies determined that this tool over predicted a patient's risk for pressure ulcer development [55]. To improve the predictive power of a risk assessment tool and ensure cost-effective nursing care, information that more closely identified patient risk for pressure ulcers was needed [45,55,66].

The Braden Scale was developed in 1987 to address the limitations of the Norton Scale. This scale was based on current research of etiologic factors that: 1) contribute to intense and prolonged pressure and 2) diminished tissue tolerance for pressure. The nurse uses the model to assign a numerical score to a patient — the lower the score, the greater the risk of pressure ulcer formation [66]. Studies have shown this tool also over predicts risk status but less than any other risk assessment tools currently available [56,65,66].

The NPUAP and the IAET guidelines grade or stage pressure ulcers based on the degree of tissue damage. While the IAET and NPUAP standards both describe nursing interventions aimed at reducing a patient's exposure to risk factors, only the IAET standards include nursing interventions for treating actual pressure ulcers.

For this project, the information derived from the analyses of these types of data sources was used in the construction of a domain-specific conceptual model. The data collection and analyses continued until the nurse-experts were satisfied the conceptual model was an accurate representation of **their** expert reasoning.

### 2.2.4. Implementation

The conceptual model includes the domain criteria, the choices associated with each criteria, and the relationships among the criteria. Developing the implementation model required identifying all combinations of the key concepts and relationships of that portion of the conceptual model selected for the knowledge base development. For this project, the implementation model was in the form of a decision table[10] representing the expert's critical decision path. The implementation model was then reviewed by the author and the nurse-experts to determine completeness, correctness and to eliminate redundancies. At this stage, the nurse-experts identified which combinations were either clinically meaningless or unlikely to occur, which were then removed from the decision table. This implementation model was then converted into a production rule knowledge representation schema executable using VP-Expert™.

Production rules are conditional **IF-THEN** descriptions of a given situation or context of a problem. Rules are best used in domains consisting of many facts, such as clinical medicine [3,8]. The **IF** clause (or premise) can describe an object, situation or position. If the premise is true, the **THEN** clause of the rule is activated. Relationships within the premise(s) can be described by the conjunctives **AND, OR** and **ELSE** which are intended to represent all possible decision choices associated with a domain.

VP-Expert™ is a rule-based expert system development tool which provides a backward chaining inference engine, user interface, knowledge base and commands needed

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[10]A decision table knowledge representation schema comprised of columns and rows that represents the exhaustive set of mutually exclusive conditions within a predefined domain.

to create a working expert system. VP-Expert™ was selected as a development tool as it is an inexpensive DOS application and relatively easy to use. As such, an expert system developed as a result of this research could be installed on the majority of microcomputers used in hospitals.

### 2.2.6. Evaluation

There is no well-defined or universal evaluation methodology for expert systems, yet ensuring the knowledge base content is correct, consistent, and complete is an essential element of expert system design. Validation and verification are techniques used both during and after the design process to confirm the completeness and correctness of the knowledge base. While validation has been described more as an operant philosophy of programming than as a discrete stage in the knowledge base development, it remains one of the main problem areas in expert system design [70,71]. Validation is defined as the determination of the correctness of the final program with respect to the users needs and requirements [70-73]. Validation is useful as a guide in determining whether the expert system is meeting its intended requirements and goals [72]. It occurs throughout the development life cycle and results in phase-specific deliverables (see Table 5).

**VALIDATION PRODUCTS**

| Development Phase | Product |
|---|---|
| Problem Definition | • project objectives |
| Knowledge Acquisition | • low level conceptual model |
| Implementation | • decision table |

**TABLE 5 VALIDATION PRODUCTS OF THE PROBLEM DEFINITION, KNOWLEDGE ACQUISITION AND IMPLEMENTATION PHASES OF THE EXPERT SYSTEM DESIGN PROCESS**

The first validation activity takes place during the Problem Definition phase where the goals and objectives of the expert system development project are defined. These serve as the foundations for the system and act as guidelines for validating subsequent stages. Throughout Knowledge Acquisition, the knowledge engineer looks for incomplete domain specifications, ambiguities and redundancies in the emerging conceptual model. The final product is a conceptual model the nurse-experts agree represents the crucial domain elements and decision-making path they follow. The implementation model is the last validation deliverable and allows the knowledge engineer, in conjunction with the nurse-experts, to check and correct any data contradictions, inconsistencies, incompleteness and redundancies. Detecting these shortcomings without some form of decision table is highly improbable whereas the format of the implementation model readily shows unreachable conclusions [73].

Verification is defined as the determination that the rule base has been written without bugs [70]. With the advent of commercially available shells, verification has become easier. Programs with tracing functions and/or filters for catching common errors in the syntax or rule redundancy have proven invaluable in knowledge bases over several dozen rules [70]. The final verification technique requires performing a small scale comparison of the knowledge base output against the recommended interventions of a nurse-expert.

These validation and verification activities test the proposed expert system under certain pre-defined conditions: that is, testing whether the domain is understood enough to be developed into a working prototype.

**VERIFICATION PRODUCTS**

| Design Stage | Product |
|---|---|
| Implementation | • production rule statements consistent with decision table |
| Evaluation | • case-based comparison of the knowledge base contents against the decisions of a nurse-expert |

**TABLE 6 VERIFICATION PRODUCTS OF THE IMPLEMENTATION AND EVALUATION PHASES OF THE EXPERT SYSTEM DESIGN PROCESS**

The ultimate test of any prototype is comparing the expert system responses to the human expert responses. As the purpose of this project was to test the concept of expert systems as adjuncts in non-expert nurse decision-making only, the final evaluation focused on the reliability of the conceptual model. To measure this, a fourth nurse-expert employed by the GVHS as a skin care specialist, was recruited. This final nurse-expert had no input into the conceptual model design and was unfamiliar with the model content. This nurse-expert's participation was in: 1) selecting patient cases representative of those patients at high risk for pressure ulcer formation and 2) using these real-life case samples to describe and explain her decision-making processes to the author[11]. The knowledge engineer then compared these verbal descriptions and observed actions against the knowledge ordering and content within the conceptual model.

## 2.3. Summary

In spite of decades of research in the development of expert systems, knowledge engineering is still an evolutionary process [19,25,27]. No formal training exists to teach or prepare potential knowledge engineers and the majority of knowledge engineers continue to develop their skills through hands-on experience [12,18,27]. The role of the knowledge

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[11]This was accomplished through interviews and direct observation as knowledge acquisition methods.

engineer includes extracting relevant knowledge from domain experts who may experience difficulty verbalizing how they apply their expertise and is considered the most challenging aspect of knowledge engineering [2,7-9,11-14]. Communication and interpersonal skills therefore, are an essential tool to the knowledge engineer.

In expert system design, development focuses on the strategies and methods used by experts in solving domain problems. Through an extended series of interactions, the knowledge engineer and experts select and define a problem suitable for expert system development, discover the basic concepts involved and develop rules that express the relationships between these concepts [12]. The goal is to use this knowledge to create an expert system capable of providing domain specific expert advice to non-experts.

An integral but often overlooked component of expert system construction is testing the contents of the knowledge base [12-14, 70-73]. While no universal evaluation methodology exists, performing verification and validation techniques can be conducted to ensure the proposed conceptual model is correct, consistent and complete [12,70-72].

# 3. RESULTS

## 3.1. Problem Definition

The first task of defining the planning and organization objectives of this project was accomplished by answering four key questions:

### 1) How suitable is the domain of pressure ulcer prevention and management for expert system application?

The incidence rates over the last decade are increasing in acute care (3% - 14%) and extended care health facilities (25% - 29%) [60-62]. After an extensive literature review and preliminary interviews with nurse-experts, it was concluded that pressure ulcer knowledge was incompletely understood and unsystematically applied to clinical practice by non-expert nurses [39,40,45]. Despite the expansion of knowledge in the areas of cause, prevention and treatment, pressure ulcers continue to be problematic [40,45,48,55]. Reasons for this continuing problem include:

- information on the prevention and management of pressure ulcers is inconsistently provided to non-expert staff nurses;
- information that is available tends to be poorly organized in binders on nursing units. The resulting long search times precludes the habitual use of the available information by non-expert nurses;
- statistics on the magnitude and significance of pressure ulcer formation are not collected and therefore, not available. The cost and impact of pressure ulcers on health care facilities and patients tends to remain unrecognized by clinical practitioners;
- staff nurses do not have a complete understanding of the clinical indicators that contribute to a patient's susceptibility to ulcer formation; and
- staff nurses are unaware of what nursing measures constitute appropriate prevention and treatment strategies.

The following quote illustrates a common scenario in the inconsistent management of pressure ulcers:

> "Nurse 7:00am-3:00pm: Treats the patient's granulating wound with moist dressing; uses Stomahesive around the wound; puts dressing on the wound, pours saline irrigant on the 4X4's and tapes the dressings to the Stomahesive edges. *Reasonable, therapeutic method of treatment.*
>
> Nurse 3:00pm-11:00pm: Removes the dressing and decides to use Duoderm, which acts as an absorbent agent and a cover; removes the Stomahesive, irrigates the wound, pats the surrounding healthy skin dry, applies the Duoderm, and secures the dressing. *Good, reasonable, therapeutic method of treatment.*
>
> Nurse 11:00pm-7:00am: Is upset because she cannot see the wound bed and would like to chart her findings; removes the tape and lifts the Duoderm away from the wound; irrigates with Ringer's lactate. Her preference is a selectively permeable membrane by Johnson & Johnson. She selects a size that will overlap the wound edges, applies the dressing, and secures the edges with tape. *Reasonable, therapeutic method of treatment.*
>
> Nurse 7:00-3:00pm (24 hours have elapsed): Becomes alarmed when she sees the yellow-brown colored liquid under the membrane; removes the membrane and is content that there is no odor. She irrigates the wound, sees that it is clean, and decides to use an absorptive powder (manufactured by Bard). She places it in the wound, puts two 4X4's over the wound, and secures the edges with tape. *Good, reasonable method of treatment."* [55, p.268].

This description highlights a common theme where even though the nursing interventions are appropriate, the inconsistent application results in disruption and delay of wound healing, as well as wasted nursing time [55].

Finally, Davies' [17] domain selection criteria for expert system development (see page 4-5), was used as a basis for determining the suitability of pressure ulcer knowledge for knowledge base development:

- nurse-experts were willing and able to commit the time to the process of developing a knowledge base;
- staff nurses tend to have limited expertise in treating pressure ulcers and virtually no expertise in pressure ulcer prevention;
- this expertise is required by non-experts. The iatrogenic nature of pressure ulcers led the NPUAP to conclude the incidence of pressure ulcers could realistically be reduced by 50% [36,45]. This is not achievable until staff nurses' can increase their own knowledge base to improve on their clinical expertise [57].

- the focus of pressure ulcer knowledge is narrow. In many cases, pressure ulcers can be assessed and treated in isolation from other biological variables or causes of hospitalization [46,60];

- non-expert nurses require this expert knowledge in their daily practice. The incidence of pressure ulcer formation has seen an increase over the last decade [45,60,64]. Interventions aimed at prevention is the best defense against pressure ulcer formation. This can only occur at the staff nurse level of clinical practice and most staff nurses tend to be non-expert in the domain of pressure ulcer activities [36,44,45]

### 2) Are nurse-experts available for the development of the knowledge base?

While the prevalent definition of an *expert* is a person who, based on training and experience, is able to do things that non-experts cannot, there is no tested method to reliably identify expert nurses [20]. For this project, the criteria for selecting nurse-experts is based on an amalgam of expert selection criteria used by researchers studying expertise in nursing. These criteria included: the expert be employed at least 2 years in the area of pressure ulcer prevention and management and at least one additional criteria from the following: 1) published article(s) on pressure ulcer prevention and management; 2) gives presentations on pressure ulcer prevention and management theory and interventions to other health care providers; or 3) is labeled an *expert* in pressure ulcer prevention and management by other nurses [20,24,74].

Clinical nurses with the required expertise in pressure ulcer activities were identified at the University of Victoria's School of Nursing and the GVHS. Three nurse-experts agreed to act as consultants for the development of the knowledge base:

- Professor J. Mantle[12];
- Ms. F. D'Arcy; and
- Ms. J. Paul[13].

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[12]Professor J. Mantle holds a joint appointment as a Professor in the School of Nursing and as a Clinical Nurse Specialist in the Juan de Fuca Hospital Foundation. Due to the high rates of pressure ulcers in extended care facilities (up to 28% incidence rates [45]), Professor Mantle is considered an expert resource for novice nurses.
[13]Ms. D'Arcy and Ms. Paul are registered nurses with advanced training in skin care for hospitalized patients. They are employed as skin care nurse experts at the GVHS and their duties also include acting as expert resources for non-expert nurses.

3) What errors do novice practitioners typically make that experts do not?

The nurse-experts identified the following errors non-expert nurses make:

- uncertainty about what type of patient data to collect and how to analyze it in order to care for patients with a pressure ulcer or at risk of developing an ulcer;
- overlooking or misunderstanding the importance of clinical indicators that place a patient at, or increase a patient's risk of, developing an ulcer;
- inconsistently applying nursing treatments to formed ulcers;
- over reliance on nurse-experts for all aspects on pressure ulcer care;
- ignorance of nursing interventions that are based on current theory or research.

4) How would an expert system reduce these errors?

To reduce or eliminate the occurrence of these errors, the nurse-experts believed a tool was required that could help non-experts develop an understanding of:

- clinical indicators increasing patient risk for pressure ulcer formation; and
- appropriate nursing interventions aimed at decreasing the risk of pressure ulcer formation.

Any tool that would help to reduce these errors would be an effective start in meeting the NPUAP goal of a 50% reduction in pressure ulcer formation. The challenges are 1) to structure and present pressure ulcer information in a format where clinically efficacious decisions could be made by non-expert nurses and 2) to communicate this information within health care facilities. Information that can be organized and presented in a format that is research based, consistent and can be directly applied to clinical practice would be an effective step in decreasing pressure ulcer formation [44,45,48,58].

The completion of this phase enabled the author and the nurse-experts to define the objectives listed in Chapter 2, Section 2.2.1.

**OBJECTIVE 1**: The scope of the pressure ulcer prevention and treatment activities targeted for expert system development are:

- assessing clinical indicators that placed a patient at risk; and
- assessing ulcer configuration characteristics.

**OBJECTIVE 2:** To identify and obtain a committment from the key players required for consultation. These key players included nurses skilled in pressure ulcer care and a physician skilled in wound classification and infection identification.

**OBJECTIVE 3:** To test the concept that an expert system can be designed as a decision-support tool for non-expert nurses in the prevention and treatment of pressure ulcers.

## 3.2. Knowledge Acquisition

A high-level conceptual model of pressure ulcer nursing activities emerged from the literature review and discussions with nurse-experts. Figure 3 represents a model of the decision-making process local nurse-experts use when assessing and applying pressure ulcer prevention and management knowledge. This process begins with an initial physical assessment where the nurse determines the presence or absence of a pressure ulcer and concludes with the implementation of interventions effective in preventing or treating a pressure ulcer. The shaded area of Figure 3 are the portions of the model (Ulcer Configuration and Assessment of Clinical Indicators[14]) selected and examined for expert system development and is shown in greater detail in Figure 4. Only the Clinical Indicator processes were used in developing a prototype knowledge base.

[14]As the value of this model includes the linking of interventions to specific ulcer characteristics and clinical indicators, considerable work was conducted in the identification of Treatment and Preventative Interventions. To date, these decision processes are partially completed.

Figure 4 highlights the key criteria associated with the decision processes selected for knowledge base development: Assess Ulcer Configuration and Assess Clinical Indicators. Each module contains the choices associated with each criteria and is presented in the order of importance as described by the nurse-experts.

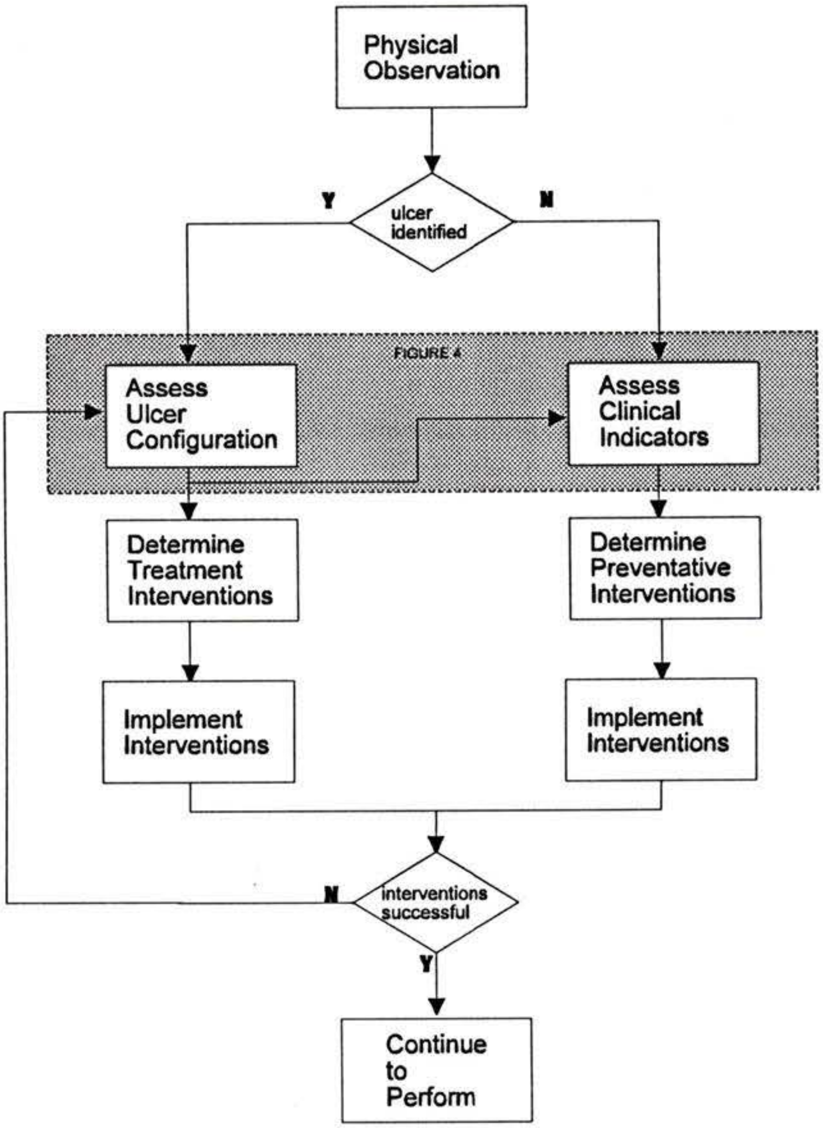


**FIGURE 3 PRESSURE ULCER ASSESSMENT AND MANAGEMENT DECISION MODEL USED IN CLINICAL NURSING BY NURSE-EXPERTS.**

The right branch represents the decision-making processes related to the assessment of clinical indicators and nursing interventions associated with an increased risk of pressure ulcer formation. The left branch represents the decision-making processes related to the assessment of pressure ulcer configuration characteristics and associated treatment interventions. Only the Assessment of Clinical Indicators within the shaded area (Figure 4) were selected for the knowledge base development.

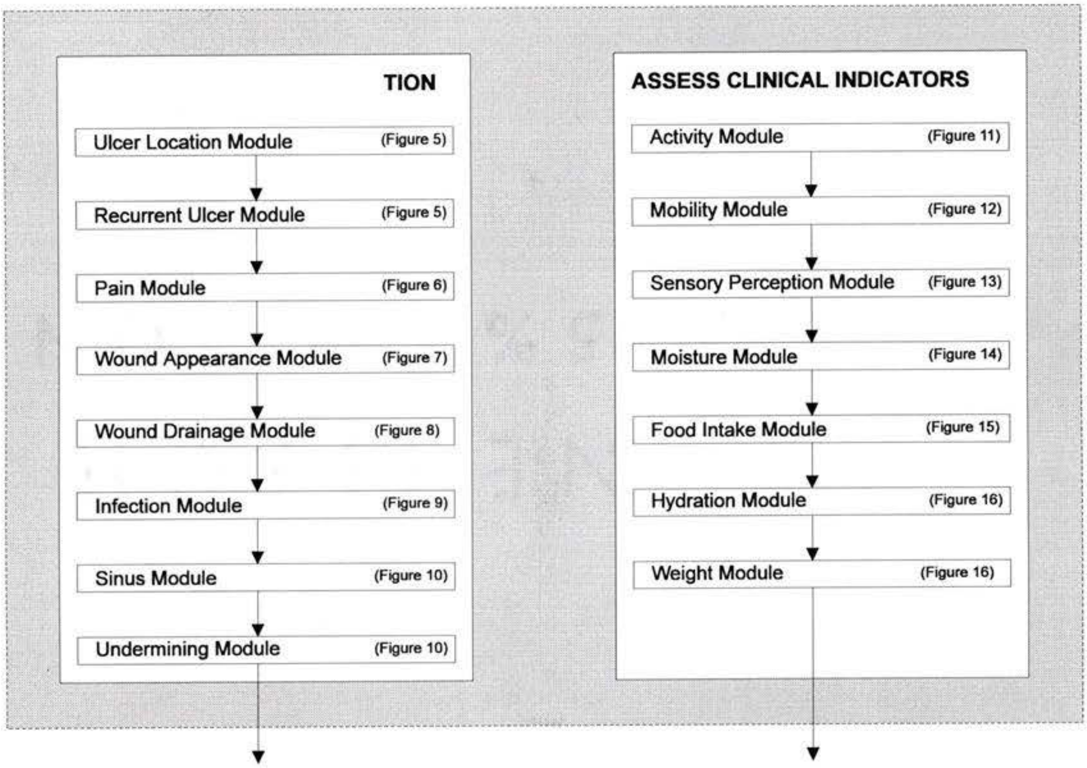


**FIGURE 4 CRITERIA ASSOCIATED WITH EACH DECISION PROCESS WITHIN THE PRESSURE ULCER NURSING DECISION MODEL SELECTED FOR EXPERT SYSTEM DEVELOPMENT**

The left branch represents the key criteria, options accompanied with each criteria and the information flow associated with Pressure Ulcers (defined as Modules). The right branch represents the key criteria, options accompanied with each criteria and the information flow associated with assessing Clinical Indicators (defined as Modules). Each module was then refined to the decision-flow level of granularity is are presented in Figures 5 - 16.

### 3.2.1 Assessment of Ulcer Configuration

The criteria associated with *Assessment of Ulcer Configuration* (identified and described in Table 5) represent the type and order of ulcer characteristics assessed and examined by nurse-experts. The ordering of these criteria reflects the logical course of consideration in the clinical decision-making process rather than the importance of criteria as presented in research. A unique and clinically crucial feature of this decision making process description is that it allows for the linking of appropriate nursing interventions to each criteria choice. This feature of knowledge representation will allow non-experts to immediately apply this information into their clinical practice.

| ULCER CONFIGURATION CRITERIA | DESCRIPTION |
|---|---|
| Location | • what is the physical location of the pressure ulcer? |
| Recurrence | • is the ulcer new or recurrent? |
| Pain | • is the ulcer painful? |
| Appearance | • what is the color of the ulcer?<br>• are muscle, bone and/or tendon visible? |
| Wound Drainage | • is there any wound drainage? Is yes, what is the color? |
| Infection | • is the presence of an infection suspected? |
| Sinus Tract | • is there a sinus tract present? |
| Undermining | • is undermining present? |

**TABLE 7 CRITERIA AND DESCRIPTIONS USED IN THE ASSESSMENT THE CONFIGURATION OF A PRESSURE ULCER**

The combination of information collected from the literature review and the knowledge elicited from the nurse-experts resulted in the creation of the low-level conceptual model of pressure ulcer activities as described in Figures 5 - 15. These figures are the detailed decision flow diagrams for each module of the *Ulcer Configuration* criteria.

The nurse-experts stated there are specific interventions associated with each key criteria. While the KA for these treatment and prevention modules remain incomplete at this time, this conceptual model allows for the inclusion of these interventions. The **Nursing Intervention** processes are where these instructions would be stored. At the completion of the Ulcer Configeration Assessment, intervention suggestions associated with specifically selected configuration characteristics are sent to and collected from the Intervention Summary process (See Figure 10).

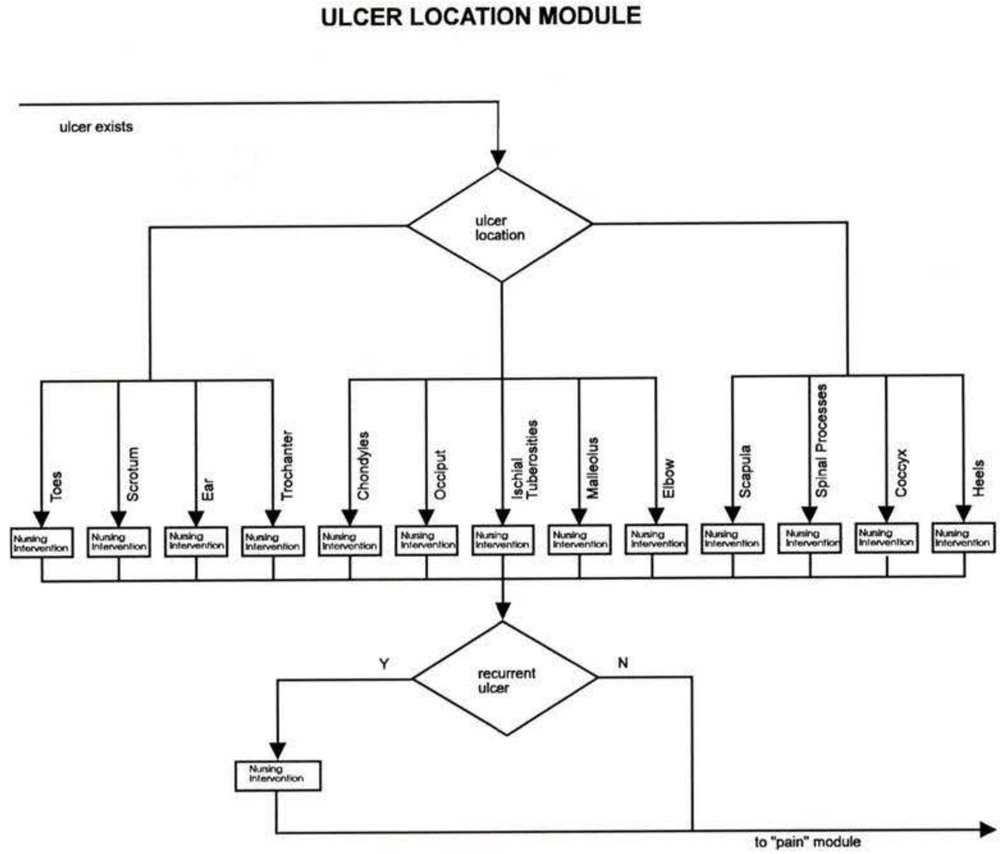


**FIGURE 5 DECISION-FLOW DIAGRAM REPRESENTING THE CRITERIA *ULCER LOCATION* AND *RECURRENT ULCER***

Diagram shows the decision path nurse-experts use when assessing *ulcer location*. Treatment interventions are prescribed according to the location of the ulcer. Assessing whether the ulcer is new or recurrent is the next decision option considered. If the ulcer is new, the decision path leads to the criterion *Pain.* A recurrent ulcer however, requires further nursing intervention before assessing *Pain*.

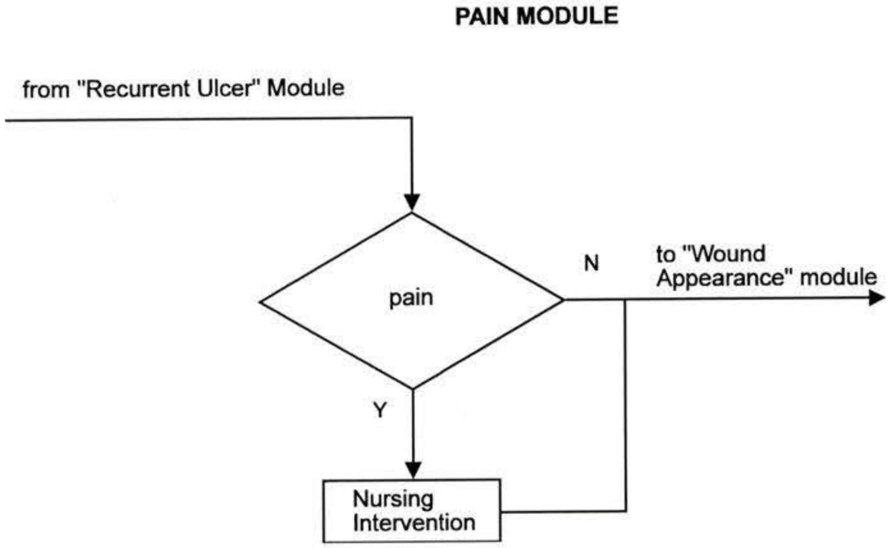


**FIGURE 6 DECISION-FLOW DIAGRAM REPRESENTING THE CRITERION *PAIN***

Diagram shows where in the assessment process the nurse-expert assesses the presence or absence of pain. While there is no intervention associated with *no pain*, the presence of pain dictates specific nursing actions. For example, if *Pain* is present, the nurse-expert will need to assess the necessity of administering any analgesia before progressing with the ulcer assessment and treatments.

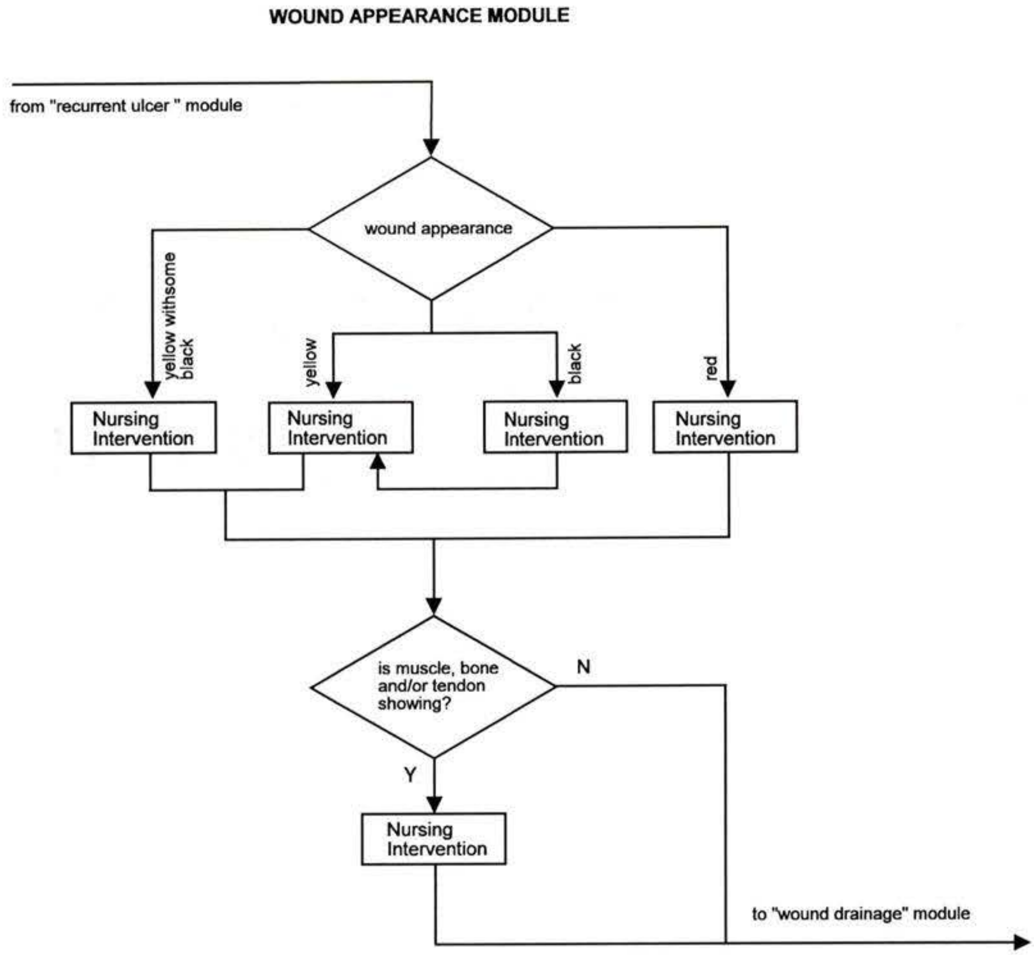


**FIGURE 7 DECISION-FLOW DIAGRAM REPRESENTING THE CRITERION *WOUND APPEARANCE***

Diagram shows the choices facing the nurse-expert in assessing the appearance of the tissue within the pressure ulcer. Each color choice is associated with the depth of the ulcer and treatment interventions are determined by the wound depth. For example, *BLACK* indicates eschar, making the depth of the ulcer impossible to determine. The appropriate intervention is have the eschar removed. Once removed, the decision-path proceeds to the choice, *YELLOW*, implementing those interventions. The nurse-expert proceeds to the assessment of whether muscle, bone or tendon are showing. Next, the nurse-expert proceeds to the *Wound Drainage* criteria.

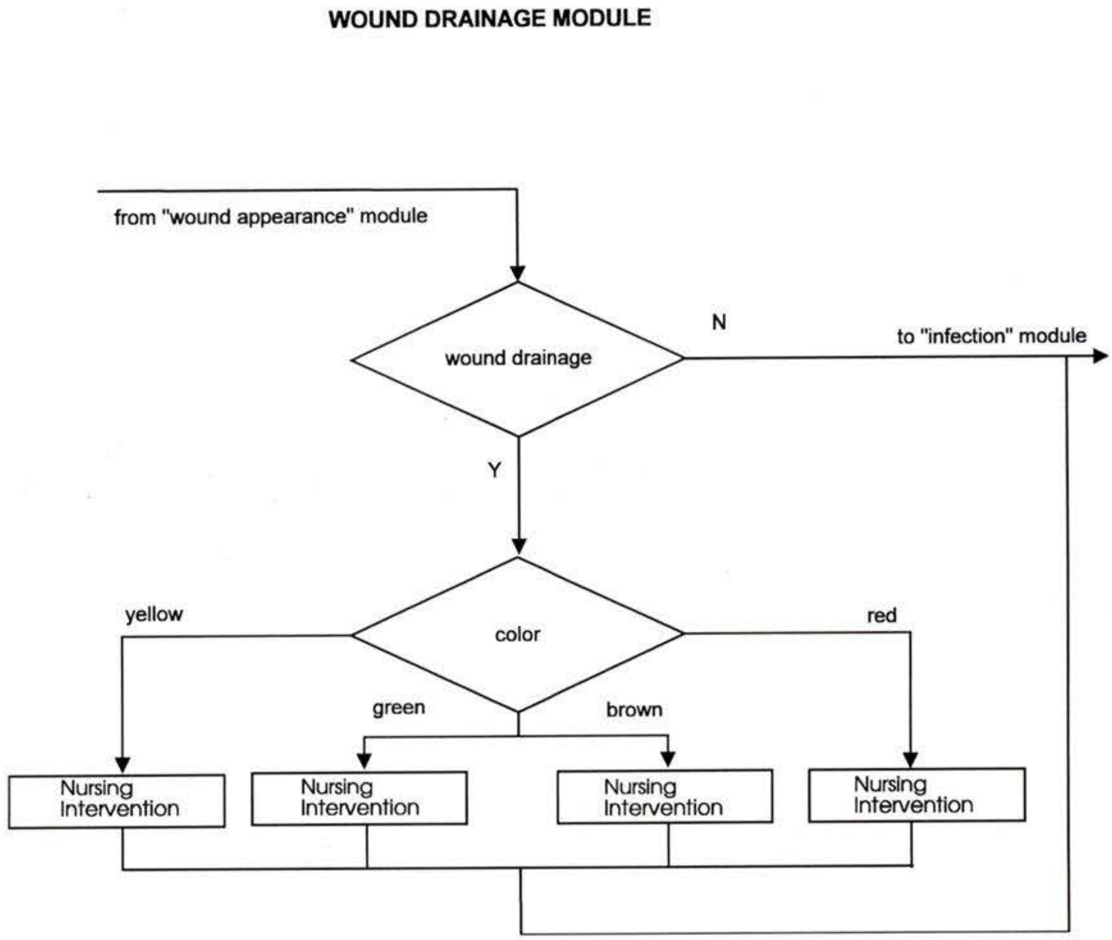


**FIGURE 8 DECISION-FLOW DIAGRAM REPRESENTING THE CRITERION *WOUND DRAINAGE***

Diagram represents the decision choices associated with *wound drainage*. If a pressure ulcer is draining, the nurse-expert must assess the quality of any drainage before selecting a specific treatment intervention. This is accomplished by determining the drainage color. For example, *RED* indicates the presence of blood, requiring a specific dressing type. For each choice, there is an appropriate wound dressing that differs from those associated with other colors.

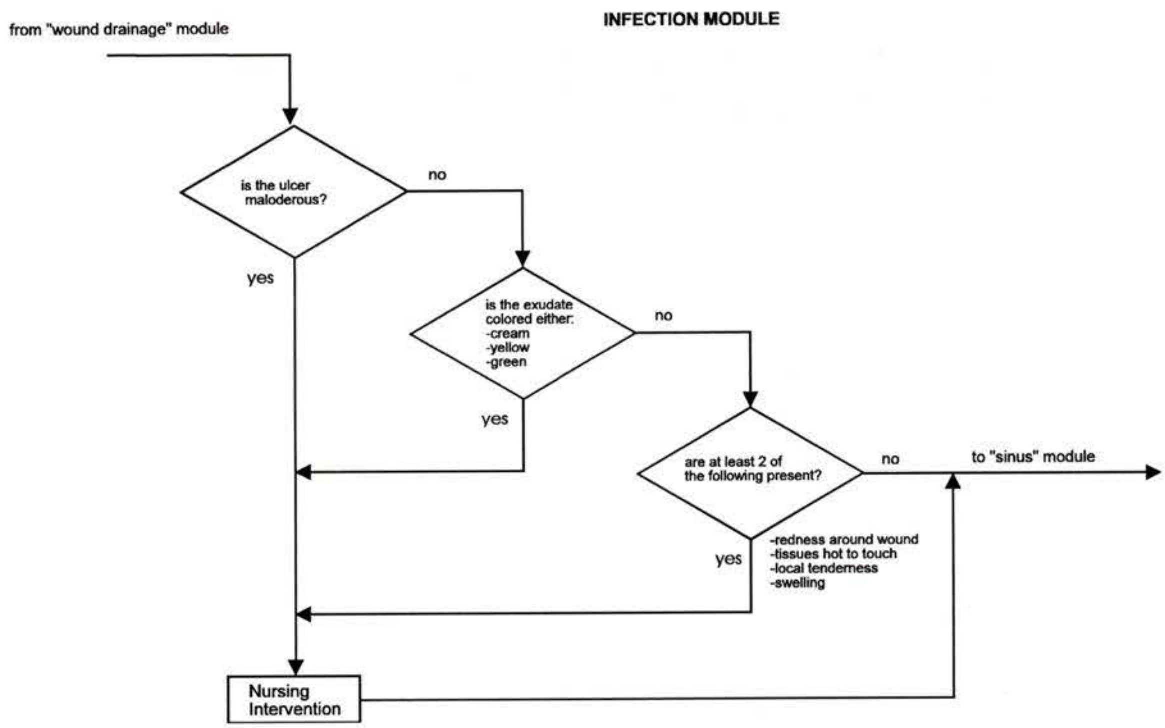


**FIGURE 9 DECISION-FLOW DIAGRAM REPRESENTING THE CRITERION *INFECTION***

Diagram indicates the choices that indicate the presence of infection of the pressure ulcer. The selection of any of these choices leads to the same treatment intervention calling for further investigation to determine the presence and type of any infecting organism.

Color is an important clinical indicator that is a source of confusion and error in clinical judgment for novices. The nurse-experts use color as an assessment choice in three different configuration criteria: *Wound Appearance, Wound Drainage* and *Infection* . The rationale and significance of color differs however, within each of these modules and provides the nurse-expert with unique data. For example, a yellow color under *Wound Appearance* refers to the color of the patient's tissue and is indicative of an ulcer extending to the subcutaneous layer. Under *Wound Drainage*, a watery yellow drainage suggests noninfectious serous drainage, while a thick yellow exudate choice under *Infection* is indicative of a staphlococcus infection.

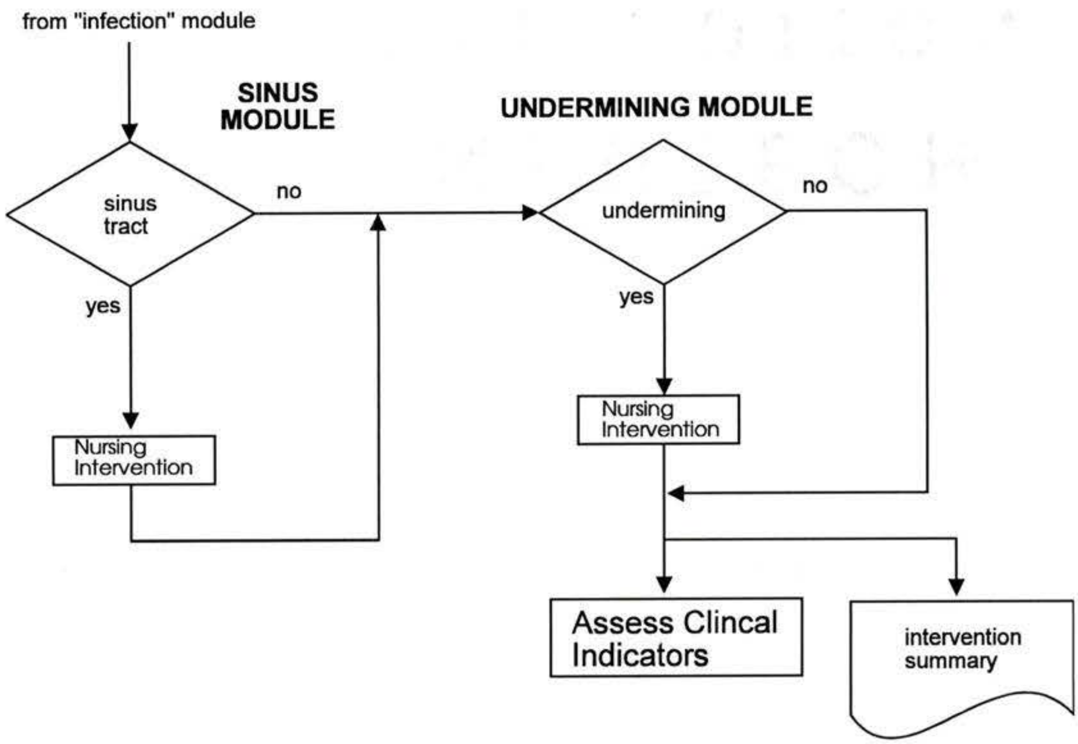


**FIGURE 10 DECISION-FLOW DIAGRAM REPRESENTING THE CRITERIA *SINUS* AND *UNDERMINING***

Diagram shows the sequence of the last final two ulcer configuration criteria. Following the assessment of the last criteria, the nurse-expert creates a patient-specific nursing care plan based on consideration of prescribed treatment interventions. Once this aspect of the patient care plan has been determined, the nurse-expert then proceeds to the assessment of the *Clinical Indicators* criteria. Once this second branch has been completed, the nurse-expert is in possession of enough patient data to implement interventions aimed at promoting ulcer healing and preventing further tissue breakdown.

Any successful treatment of pressure ulcers requires not only caring for the ulcer, but also reducing or eliminating those factors that placed the patient at risk. If these factors are not reduced or removed from the patient's environment, wound healing may be delayed, the ulcer may worsen and/or other ulcers may develop. An assessment of *Clinical Indicators* is initiated therefore, after two events: 1) when a physical assessment reveals no pressure ulcer or 2) after the *Ulcer Configuration* assessment is completed (See Figure 3).

### 3.2.2 Assessment of Clinical Indicators

There is universal agreement among researchers and clinical nurse-experts that the critical determinants of pressure ulcer prevention and/or formation can be classified as those factors that are: 1) primary etiologic criteria contributing to prolonged and intense pressure; and 2) secondary etiologic criteria contributing to a decreased tissue tolerance for pressure [57,61]. The clinical experiences of the nurse-experts used for this project have extended this theory by adding that primary *Clinical Indicators* must be identified and relieved before secondary *Clinical Indicators* if a pressure ulcer is to be prevented and/or healed. Table 8 outlines and describes those key *Clinical Indicators* that increase a patient's risk for pressure ulcer development.

| CLINICAL INDICATOR CRITERIA | DESCRIPTION |
| --- | --- |
| Activity | • is the patient motivated and physically able to ambulate? |
| Mobility | • is the patient able to shift the position of their body? |
| Sensory Perception | • is the patient able to physically respond to pressure related pain or discomfort? |
| Moisture | • what is the frequency which the patient or bed linen feels moist? |
| Food Intake | • what percentage of each meal the patient is able to consume? |
| Hydration | • is the patient's fluid intake adequate? |
| Weight | • is the patient's weight under or over/ideal? |

**TABLE 8 CRITERIA AND DESCRIPTIONS USED IN ASSESSING THE CLINICAL INDICATORS ASSOCIATED WITH AN INCREASE IN PATIENT RISK FOR PRESSURE ULCER DEVELOPMENT**

Activity, Mobility and Sensory Perception are primary etiologic criteria and Moisture, Food Intake, Hydration and Weight are secondary etiologic criteria.

Figures 11 - 15 are the detailed decision flow diagrams for each module of the *Clinical Indicators* criteria. At the completion of the Clinical Indicators Assessment, intervention suggestions associated with selected criteria are sent to and collected from the Intervention Summary process (See Figures 13 and 16).

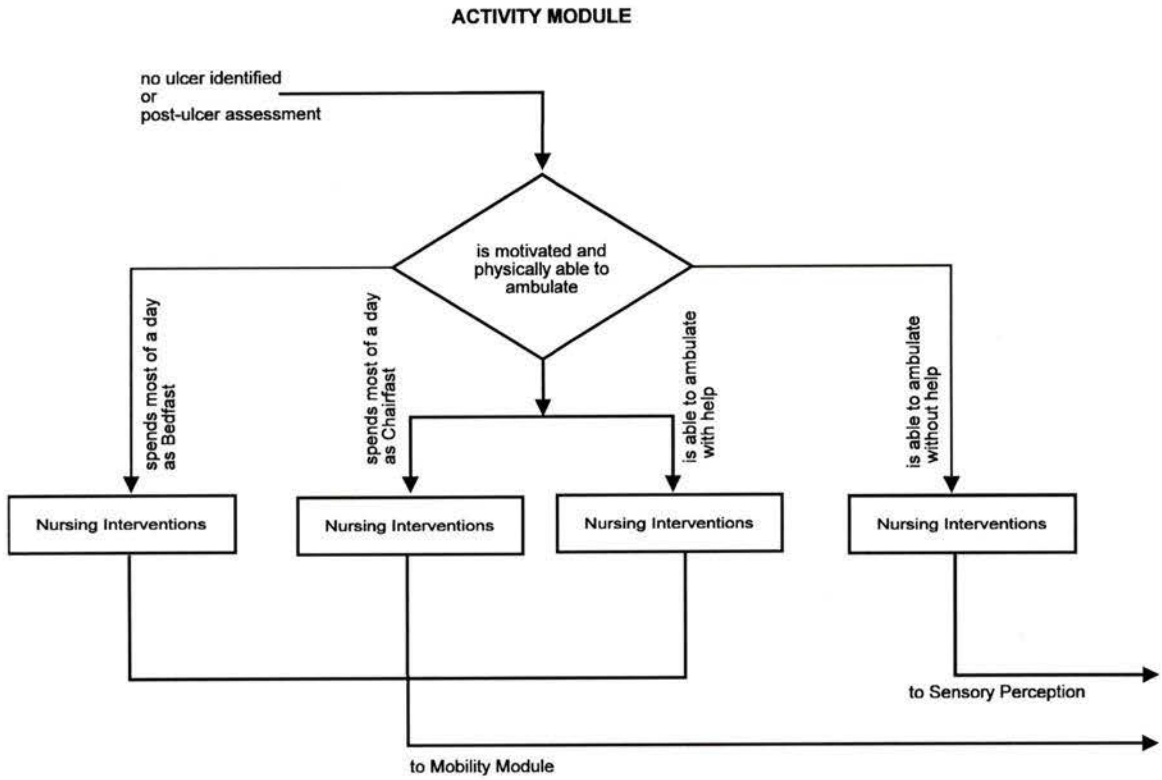


**FIGURE 11 DECISION-FLOW DIAGRAM REPRESENTING THE CRITERION *ACTIVITY***

Diagram shows the choices considered when assessing the criterion *Activity* and the decision path followed once the appropriate nursing intervention has been identified. The nurse-expert selects the choice that most closely reflects how a patient spends the majority of a day. When any choice other than *ambulates without help* is selected, the next criterion to be considered is *Mobility*. If the choice *ambulates without help* is selected, *Mobility* is bypassed and the nurse-expert moves on to *Sensory Perception* .

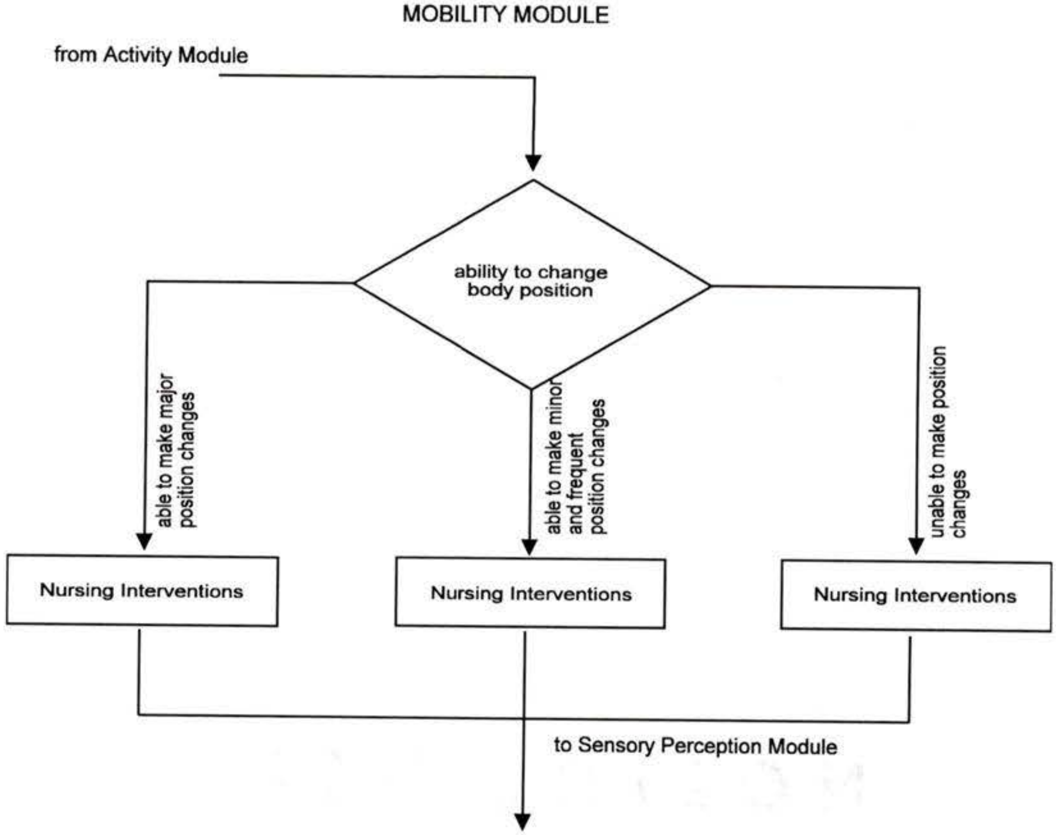


**FIGURE 12 DECISION-FLOW DIAGRAM REPRESENTING THE CRITERION *MOBILITY***

Diagram shows the decision choices associated with *Mobility* and the decision path followed after nursing interventions are determined. *Able to make major shifts* refers to a patient's capacity to shift when the tissue's tolerance for pressure has been reached. *Minor shifts* refers to the patient's ability to make small position shifts in response to tissue pressure.

**SENSORY PERCEPTION MODULE**

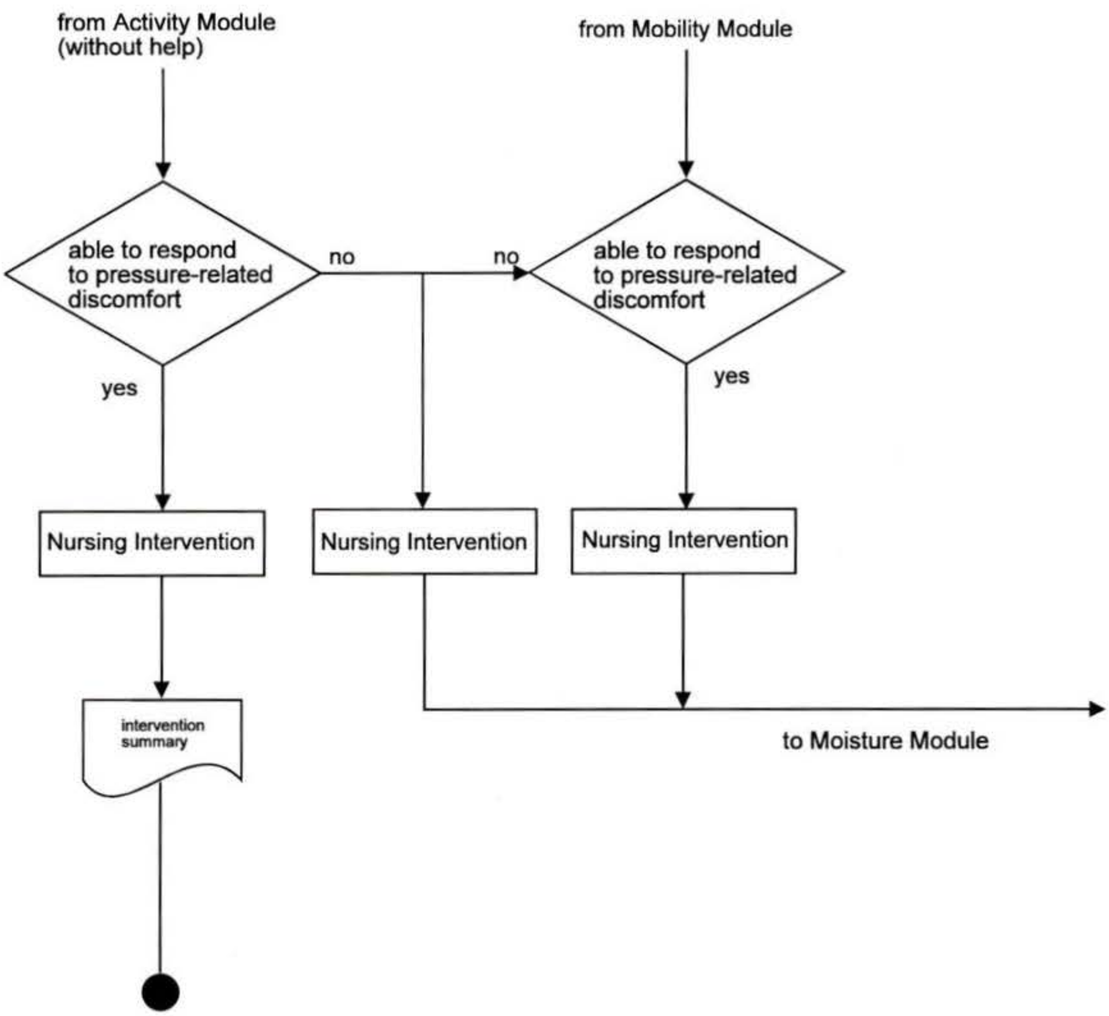


**FIGURE 13 DECISION-FLOW DIAGRAM REPRESENTING THE CRITERION *SENSORY PERCEPTION***

Diagram shows the decision path of the nurse-expert when assessing a patient's ability to perceive and respond to pressure-related discomfort. The inability to respond to pressure related discomfort may result from a variety of causes such as diminished cutaneous sensation or alterations in a patient's level of consciousness. When a patient is *able to ambulate without help* and *able to respond to pressure related discomfort,* they are not considered at risk for pressure ulcer formation and no further assessment is required. For a patient with impaired sensory perception, the nurse-experts must proceed to the assessment of those secondary clinical indicators that impact on the tissue's tolerance for pressure.

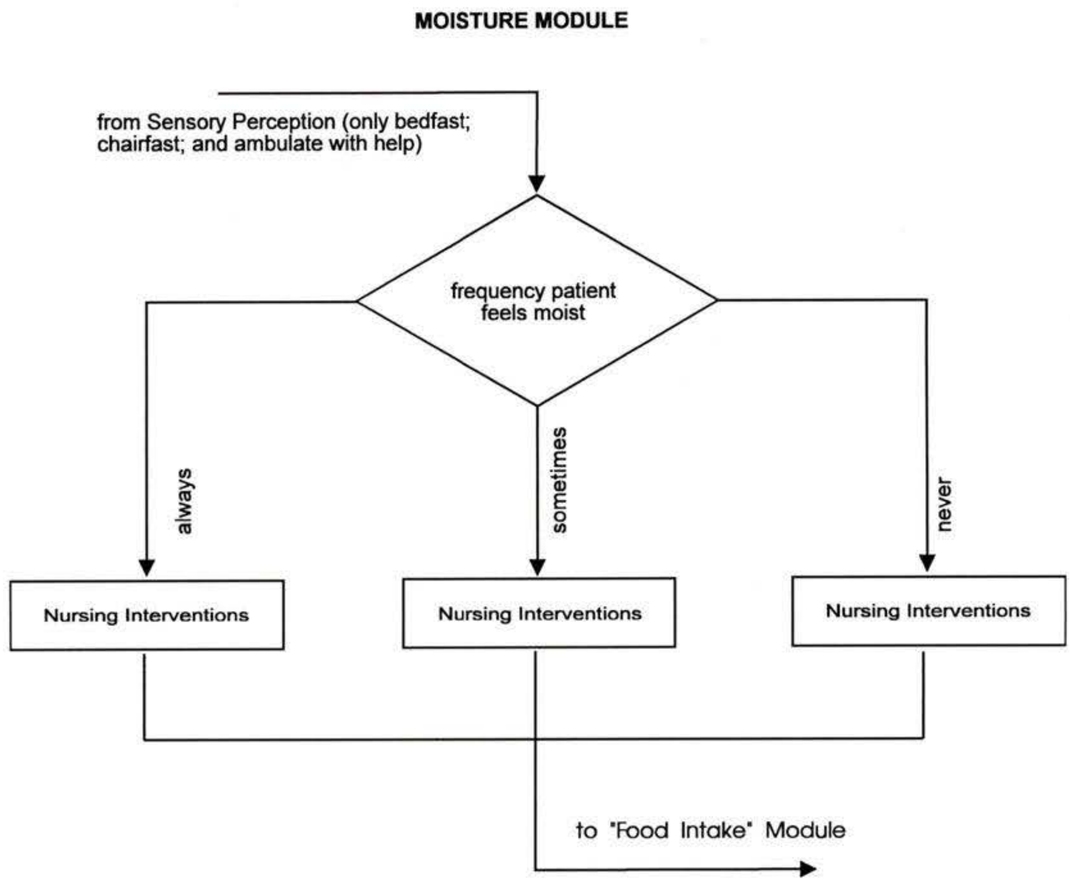


**FIGURE 14 DECISION-FLOW DIAGRAM REPRESENTING THE CRITERION *MOISTURE***

Diagram shows the decision path followed when assessing the degree and frequency a patient is exposed to moisture. *Moisture* can result from urinary or bowel incontinence, wound or abscess drainage and/or diaphoresis. The frequency that a patient's skin or linen feels moist will impact on the frequency and type of nursing interventions required to minimize the risk of moisture-induced skin maceration.

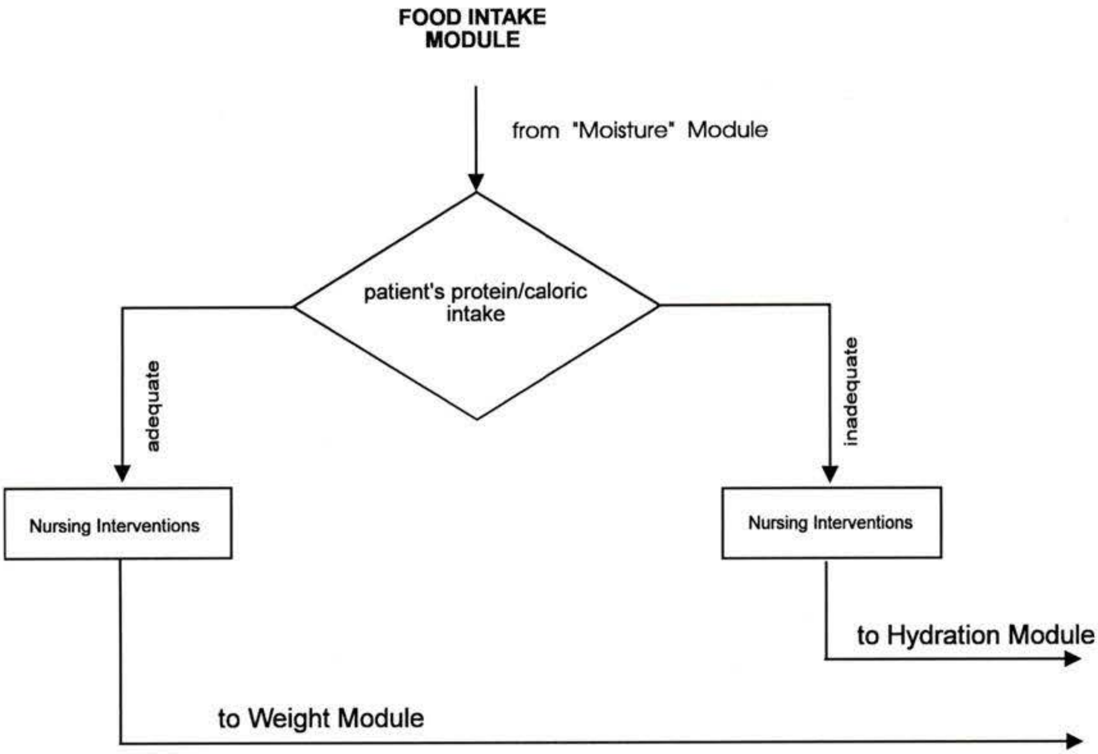


**FIGURE 15 DECISION-FLOW DIAGRAM REPRESENTING THE CRITERION *FOOD INTAKE***

Diagram shows the decision path nurse-experts follow when assessing the adequacy of a patient's usual caloric and protein intake. Food intake is considered *adequate* when at least two-thirds of each meal portion is eaten. If *Food Intake* option selected is *adequate*, then there is no need to assess *Hydration*.

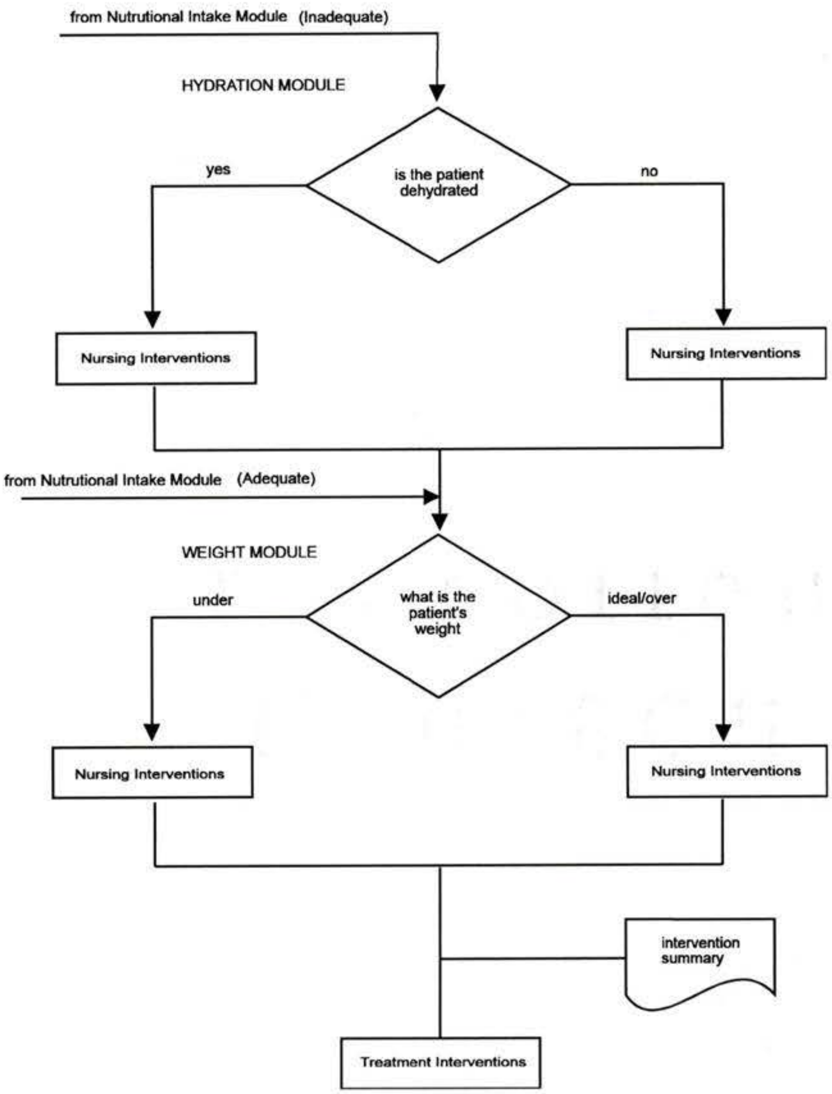


**FIGURE 16 DECISION-FLOW DIAGRAM REPRESENTING THE CRITERIA *HYDRATION* AND *WEIGHT***

Diagram shows the decision path followed when assessing the presence or absence of dehydration in a patient if a patient's food intake is *inadequate*. When considering body weight, ideal or over weight are not differentiated as the nursing interventions are the same. The frequency of *Clinical Indicator* assessments is determined by the combination of clinical indicators present as well as the nurses clinical judgment.

This detailed conceptual model served two purposes: 1) it was a mechanism for the knowledge engineer and the nurse-experts to validate the accuracy and ordering of the domain criteria and choices and 2) it was the basis for the development of an implementation model suitable for the knowledge base of the expert system shell.

## 3.3. Implementation

Controversies and conflicting opinions remain about how best to treat a pressure ulcer. There is however, no disagreement that prevention is of the utmost importance and appropriate nursing care is the critical element in pressure ulcer prevention. For this reason, the prototype modules selected for implementation were the *Clinical Indicators* and *Prevention Interventions*. Converting this branch of the conceptual model into a format suitable for implementation onto the VP-Expert™ knowledge base was a two step process. First, a decision table was created. Second, the decision table was transformed into a production rule schema.

The unique combination of all possible *Clinical Indicators* criteria and choices resulted in an seven column and 596 row decision table, where the columns represent the criteria and the rows represent the possible combinations of each criteria choice. As validation of the decision table progressed, inaccurate, impossible or unlikely combinations of clinical indicators were identified and modified or removed. A revised and final decision table was created representing 343 possible clinical combinations, part of which is listed in Appendix E. This table is comprised of columns representing the seven clinical indicators with the addition of an eighth column representing the interventions appropriate to each combination. The final decision table was rewritten onto the VP-Expert™ knowledge base in the form of **IF-THEN** statements (partially listed in Appendix F).

## 3.4. Evaluation

Evaluation is an essential component of expert system development if potential users are to be convinced of the benefits of its use [80]. Evaluations are performed throughout the KE phases to ensure that the content and structure of the conceptual model accurately reflects the knowledge and decision-making processes of the domain experts. With the knowledge engineer and the nurse-experts working together, validation and verification products had been completed for the Problem Definition, Knowledge Acquisition and Implementation phases. As part of the Evaluation phase, a final verification of the conceptual model was performed to confirm the accuracy of the low-level conceptual model (Figures 5 - 16). This was accomplished by comparing the model against the actual practices of an expert nurse practitioner.

A fourth nurse-expert[15] was recruited as a consultant for this verification. This nurse was selected for the following reasons: 1) she met the criteria for nurse-expert designation and was an experienced clinical practitioner; 2) she had not participated in the KE phases; and 3) she had no knowledge of the content or structure of the conceptual model presented in this paper.

First, patients designated *at risk* for pressure ulcer formation were selected by this nurse-practitioner. The case histories of four patients currently being treated by this nurse for pressure ulcer prevention were examined. Second, the nurse's decision process related to pressure ulcer prevention for each case were described[16] to the knowledge engineer through interviewing, open ended questioning and direct observation. Third, the nurse's system of decision-making for each case history was then compared against the conceptual model.

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[15]Ms. Wood is a colleague of Ms's. Paul and D'Arcy. She is a registered nurse with advanced education and experience in skin care for hospitalized patients. She is employed in the GVHS as an ET nurse responsible for pressure ulcer care. Her duties include acting as a resource for non-expert nurses.

[16]The nurse-practitioner was not asked to justify any action or decision, but rather to only report as accuartely as possible how she applied her expertise.

This was to verify that the *Clinical Indicator* assessment methodology modeled in Figures 11-16[17] is consistent with actual expert-nursing practice

The nurse-practitioner's patient care planning involves two main steps: 1) a review of available patient data; and 2) an interview with, and/or a physical assessment of the patient. After a ward formally requests the services of the Enterostomal Department, the nurse first reviews the medical chart for diagnostic data related to the pressure ulcer risk, reason(s) for hospitalization and contents of the nursing history. The bedside nurse, if available, is also interviewed to verify the chart information is accurate and up-to-date and to add any further information about the reasons for the consult request. If the bedside nurse is unavailable, the ET nurse continues on to Step 2 of the patient assessment.

The purpose of the second step is further data collection that will confirm that the chart information and the nurse-practitioner's initial impressions are correct. Data collection does not occur in a standardized format, but rather it is collected as it is observed by the nurse or presented by the patient. This order of data collection does not represent the importance of the data or the order in which it is considered. It is during the analysis of this data however, when the nurse-practitioner ranks her observations.

Tables 9 and 10 described an actual patient case[18] and the type of data collected in Step 1 and Step 2. The nurse-practitioner described this patient (designated as *PATIENT A*) as representative of the type of patient she is frequently called upon to assess. Once collected, the clinical data is ranked in order of importance. The determination of what deficits are present is then made, followed by the design and implementation of a patient-specific nursing care plan aimed at minimizing the impact of these deficits. If no deficits exist, the consultation ends and no further nursing actions by the nurse-practitioner are carried out.

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[17]Only the pressure ulcer prevention criteria of the model was compared with the clinical practice of this nurse practitioner.

[18]Although four case histories were reviewed, only one was presented in this thesis. This case was selected by the nurse-practitioner as representative of the patient profiles she is asked to consult on.

**STEP 1 REVIEW PATIENT DATA**
**PATIENT *A***

| DATA TO COLLECTED | PATIENT DATA |
|---|---|
| PATIENT DIAGNOSIS | --cardiac disease;<br>--diabetes;<br>--renal failure; |
| REASON FOR HOSPITALIZATION | --syncopal attack resulting in an MVA; |
| NURSING HISTORY | --patient previously hospitalized (approximately 1 year ago) which resulted in a pressure ulcer that took 6 months to treat and heal; |

**TABLE 9 ACTUAL PATIENT DATA COLLECTED THROUGHOUT STEP ONE AS PART OF THE PRESSURE ULCER PREVENTION ASSESSMENT CONDUCTED BY THE NURSE PRACTITIONER**

The nurse-practitioner used this preliminary data to develop a general picture of the patient. For example, a previous pressure ulcer that required 6 months to heal indicated there may be an urgency for early implementation of preventative interventions. The data *Syncopal Attack* and *Cardiac Disease* alerted her to potential ambulation and sensory perception deficits. The next step is to speak with the patient to verify this data and to determine the presence and extent of any deficits that place this patient at risk for developing a pressure ulcer.

**STEP 2 INTERVIEW/PHYSICAL ASSESSMENT**
**PATIENT *A***

| NURSING ACTIONS/QUESTIONS | PATIENT DATA |
|---|---|
| IS THE PATIENT UP AND ABOUT? | --patient was found resting on his bed;<br>--he relates that he is able to ambulate at will;<br>--being 'up at will', the patient is able to effectively shift body positions; |
| FEEL THE PATIENT'S SKIN AND LINEN. | --patient able to feel the nurse touching his feet;<br>--skin and linen feel dry to the touch; |
| OBSERVATION OF PATIENT'S APPEARANCE. | --patient appears well-groomed and clean;<br>--lips not dry;<br>--appears slightly overweight; |

**TABLE 10 ACTUAL PATIENT DATA COLLECTED THROUGHOUT STEP TWO AS PART OF THE PRESSURE ULCER PREVENTION ASSESSMENT CONDUCTED BY THE NURSE PRACTITIONER**

The patient data presented in this table is listed in the order it was collected by the nurse-practitioner. In her post-assessment analysis however, the data is analyzed in the order of importance. In spite of the patient's diagnosis and reason for admission, finding out the patient was able to ambulate indicated there were no *Activity* or *Mobility* deficits. Feeling the patient's skin and linen indicates the degree of *Moisture* the patient is exposed to. Confirmation that the patient is able to feel the nurse touch his feet tells her that no *Sensory Perception* deficit exists. The observation that the lips are not dry and that the patient is slightly overweight suggests that *Food Intake, Hydration* and *Weight* are adequate. This provided the nurse-practitioner with all the data required to assess whether the patient was at risk for developing a pressure ulcer. In this case, it was determined there was no risk.

## 3.5. Summary

The process of knowledge acquisition was more complex than originally anticipated for two reasons. First, the nurse-experts experienced enormous difficulty in differentiating their experiential knowledge from the theoretical knowledge of pressure ulcer prevention and management concepts and in articulating that knowledge. While written nursing standards, in particular the Braden Risk Assessment Scale, were used by the experts as foundations for verbal discussions, the nurse-experts had never before defined or verbalized the cognitive processes or the fundamental concepts of pressure ulcer management with the precision required for Knowledge Acquisition. Second, as Knowledge Acquisition progressed, it became clearer to the knowledge engineer and the nurse-experts that there was a gap between what the experts **said** they did and what they **actually** did. The consistent application of an amalgam of KA techniques that have been proven successful in KE in other disciplines resulted in the capture of the nurse-expert's clinical knowledge. These decision-making processes, represented in a conceptual model, has been validated as an accurate representation of clinical expertise.

# 4. DISCUSSION

## 4.1. Knowledge Engineering Methodology for Nursing

Knowledge engineering is a time consuming process. While tools such as expert system shells have greatly reduced development time, knowledge acquisition continues to be the greatest challenge and most time consuming aspect of knowledge engineering [3-5]. Widespread use of expert systems remains retrained by the lack of standard methods and theories of KA [3,13,16,19,21-23].

Researchers such as Dreyfus [13], Benner [24] and Tanner [74] believe that **intuitive** understanding, (defined as understanding without rationale), is an integral component of expertise and specifically, of nursing-expertise. These researchers concluded that experts will always be unable to verbalize their intuitive knowledge, and therefore it will always be inaccessible to the knowledge engineer regardless of the evolution of KA methodologies [20]. Successful expert systems require that a domain expert's knowledge and decision-making processes be made explicit. The conclusions of these researchers suggest that KA and the pursuit of expert system development is a futile exercise. Yet expert system development continues to be pursued in nursing [20,33].

There are three principal challenges that continue to slow the evolution of KE in nursing: 1) the knowledge and skills that represent clinical nursing expertise have not been clearly defined by the nursing profession, making the identification of nurse-experts difficult; 2) clinical nurse-experts are frequently excluded from the problem definition and knowledge acquisition phases of KE; and 3) retrospective analysis tends to be the method of choice used in knowledge acquisition in nursing [20,24,30-35,46,74-76]. The result has been that opportunities to adequately describe and represent expert-nursing knowledge and decision-making processes used in clinical patient care have been limited [20,24,33].

That experts cannot reliably report their experiential knowledge directly is unequivocal [4,5,7,13,17-20,22,23]. Knowledge engineering in nursing cannot advance however, when nurse researchers continue to discredit or dismiss expertise research and knowledge engineering methods that have proven successful in other disciplines [20,24,74]. For example, studies have shown that when nurse researchers use retrospective analysis is the sole method of knowledge acquisition, an incomplete picture of the domain knowledge will result [20,22,23]. Incorporating successful KA methods used in other disciplines therefore, is critical if expert system development, including this project, is to proceed in nursing .

A primary outcome of this project has been the development and testing of a multi-method knowledge acquisition technique aimed at identifying and eliciting the knowledge and skills of clinical nurse-experts. This KA technique (outlined in Table 9) is an amalgam of existing KA methods that have been used successfully in the development of expert system in other disciplines for eliciting intuitive or implicit knowledge [8,12-14,18-21,24-27,52].

| **KNOWLEDGE ACQUISITION TECHNIQUE** |
|---|
| Literature Review |
| Protocol Analysis<br>--Domain Expert Interviews<br>--Observation<br>--Current Nursing Standards of Care |
| Effective Communication Techniques |

**TABLE 11 AMALGAM OF KNOWLEDGE ACQUISITION TECHNIQUES DEVELOPED FOR KNOWLEDGE ACQUISITION IN NURSING**

The systematic application of these KA methods resulted in the creation of a conceptual model combining both research results and the theoretical and experiential knowledge foundations of the clinical nurse-experts. An extensive Literature Review and examination of Current Standards of Nursing Care enabled the author to: 1) develop a broad understanding of pressure ulcers; 2) identify and define a common language and definitions of the domain; and 3) to use this newly acquired information as a guide in the question development for subsequent nurse-expert interviews.

The importance of and need for the agreement of a standard language and consistent definitions is demonstrated in the following example. The significance of a patient's ability to ambulate in pressure ulcer prevention cannot be over-emphasized, yet some researchers present this *Clinical Indicator* assessment criteria in a manner where meaning is blurred by context. To illustrate, some nurse researchers include *level of consciousness* and *coma* as independent factors requiring assessment [64,69], yet the inclusion of these variables can impair the nurse's ability to correctly interpret and fit patient data into a pressure ulcer decision-making formula. The **cause** of altered levels of consciousness or coma will not be irrelevant to all aspects of a patient's nursing care needs, but it is in relation to pressure ulcers. The relevance these variables have on pressure ulcer prevention or formation is in their impact on the patient's *Activity* and/or *Mobility* status. By agreeing on a unique definition of *Activity* as *a patient is motivated and physically able to ambulate*, and *Mobility* as *a patient is able to change body position*, irrelevant contexts such as **causes** of coma or altered level of consciousness are removed. Any impairments to a patient's activity or mobility then, become assessed as effects independent of cause. By designing a conceptual model in this fashion, non-expert nurses are now guided to collect and assess patient data using the same decision-making formula as the domain experts.

The combination of Interviewing and Observation proved effective methods for eliciting experiential expert knowledge. The use of these methods also provided an opportunity for a comparison of the nurse-expert's verbal task descriptions and their actual performance. For example, using Interviewing, the nurse-experts reported that their assessment of *Sensory Perception* followed the same choices as set out in the Braden Scale (Appendix C). In post-Interview analyses however, there were discrepancies noted between what the experts reported as their theoretical basis for clinical practice and what they described on retrospective patient case-based reporting. Observation was able to confirm this inconsistency with actual task performance. The experts were challenged to explain the impact the Braden Scale *Sensory Perception* choices (*completely limited, very limited, slightly limited* and *no impairment)* had on decision-making and expert nursing practice. It became clear to the experts that these choices did not accurately represent their cognitive processes. After considerable discussion and re-evaluation, the nurse-experts were able to unanimously confirm that the importance in assessing a patient's ability to respond to pressure related discomfort and the determination of appropriate nursing interventions lay in the outcome of a binary choice — yes or no. In reality, all subsequent decisions and interventions related to sensory perception were based solely on whether a patient could or could not respond to pressure related discomfort.

The importance of communication skills in knowledge engineering cannot be overemphasized [8,18,20,27,52]. A knowledge engineer unable to establish a strong rapport with the domain expert is unlikely to design or build an effective expert system [18, 27]. The knowledge engineer then, has a responsibility to use communication skills that will enhance the effectiveness of the knowledge engineer-expert relationship. To illustrate, in the first interview it became clear that while the nurse-experts had taught pressure ulcer prevention and management strategies to other non-expert health care providers in the past, they had never articulated their expertise in as detailed and systematic a manner as required for KA. In these first interviews, the nurse-experts used the Braden Scale (Appendix C) as a framework for discussion as they believed this model accurately reflected the content and processes of their clinical decision-making. As KA progressed however, the limitations of this paradigm became evident. When challenged to define and justify the emerging conceptual model, the nurse-experts realized that tools such as Braden's Scale in fact, did not adequately reflect the sequence nor the criteria and choices associated with their own decision-making. When using this paradigm as a framework for decision-making, clinical data always required further analyses before decisions and interventions could be made and applied. The realization that the depth of exploration needed to accurately elicit their expertise combined with the recognition of the need to adjust their own beliefs of the value of their nursing tools was a source of enormous frustration for the nurse-experts. As a result, an environment had to be created where the nurse-experts felt motivated, comfortable and safe enough to re-examine and refine their own personal frames of reference to fully discuss pressure ulcer prevention and management. The impact of this realization was that KA was considerably longer and more difficult than originally anticipated. In retrospect, this is not surprising. The transfer of specialized nursing knowledge has been slow for at least three reasons: 1) nursing knowledge tends to be based on a tradition of oral and/or practical application rather than on a well-developed theoretical basis; 2) there is a gap between theory and nursing practice; and 3) the nursing profession's lack of experience is verbalizing and documenting nursing expertise.

KA in nursing however, is not a futile exercise. This project has shown that the thoughtful and systematic use of multi-methods for KA can produce a conceptual model of expert clinical nursing practices. Through the use of communication techniques such as those outlined in Section 2.2.3.2. (Nursing Protocol Analyses), knowledge acquisition was able to productively move forward until a complete picture of pressure ulcer prevention and management activities emerged that the nurse-experts believed was an accurate reflection of their domain expertise (See Figures 3 and 4).

### 4.1.1. Constraints on Nursing Expert Systems

Computing in health care continues to consist largely of auditing or monitoring systems rather than decision support [79]. To some extent, this has been due to limited resources and the proliferation of incompatible and isolated systems, yet these constraints are becoming less important as the price of hardware and software falls. The two basic constraints that continue to limit or delay the application of expert systems in nursing are: 1) the use of computers in clinical nursing represents a fundamental change in practice; and 2) the uncertainty associated with whether expert systems truly emulate nursing expertise [20,33,79].

Expert system use in clinical practice can be psychologically threatening as it has an impact on the view the professional care givers have of themselves [79]. The use of computers in nursing practice involves a change in how nurses think about and carry out their nursing tasks. This can lead to a misunderstanding of the role of the practitioner and the expert system — that the autonomy of the nurse is threatened when their decisions are viewed as inferior to the decisions of a computer or if disagreement exists between what the nurse decides is the appropriate course of action and what the expert system advises. This gives rise to questions of responsibility and reliability: does the non-expert nurse have a duty to consult and conform with the solution proposed by the expert system? If the non-expert nurse fails to act on the advice of the expert system resulting in the patient being inadequately or inappropriately treated, what are the consequences? The answers to these questions will depend on the proven efficacy of the expert system in question.

Related to the issue of computers representing a change in nursing practice is the question of how a domain is selected for expert system development. In order for any expert system to be an effective consultant, the nurse-user group must be included in answering the pivotal question of what problem(s) do nurses require help in solving? A system may be developed to solve pre-defined domain problems, but if it fails to help the user solve the particular problems they encounter, the system will not be used and consequently, will have no impact on their practice.

Questions have been raised regarding the reliability of expert system. Correct or appropriate action in a particular situation is usually a matter of opinion. Since the best an expert system can do is to imitate human experts who themselves are never always right, can one expect an expert system to perform better than this? For example, a physician is not expected to diagnose with 100% accuracy. Can or should an expert system be expected to perform better than the human expert the system is modeled after? This raises the unanswered question of what level of performance should a human, and hence an expert system, attain to be considered expert or competent to practice their craft? How would the competence of an expert system be accurately evaluated? Who would be responsible in the event of an adverse patient outcome — the individual practitioner or the software developer?

Expert system development is proliferating in nursing, yet the knowledge acquisition methods that guide expert system development in other fields are not always applied to nursing expert systems [20,30-35]. Nursing researchers and knowledge engineers have tended to seek sources of expertise in nursing faculty and/or nursing textbooks and it can be questioned whether these sources are in fact, expert teachers rather than expert clinical nurses [20,31,33,34,75]. While much has been written of the problems associated with knowledge engineering in nursing expert systems, there has been a failure to address the necessity of identifying and studying clinical nurse experts when developing these systems [20,33]. There remains a need to study and establish reliable and valid techniques for identification of nurses expert in diverse clinical practices. The development and application of KE techniques may act as a catalyst for the nursing profession to analyze and document its own clinical activities and how they are performed by nurse-experts.

## 4.2. Conceptual Model of Pressure Ulcer Prevention and Management

Providing skilled nursing care requires the application of well-planned interventions based on theoretical and experiential expert knowledge. In nursing practice however, there is a delay in the dissemination of research findings to clinical practice [36,78]. A contributing factor to this knowledge gap are clinical nurses who have not been careful record keepers of their own clinical experiences and practical learning [20,24,33]. The lack of amalgamation between research and clinical practice is confirmed and obvious when comparing the theoretical paradigms or standards of pressure ulcer prevention and management against the expertise and practices of local nurse-experts.

Preparatory to developing a conceptual model of pressure ulcer activities, an understanding of the current nursing paradigms of pressure ulcer prevention and management activities was required. This was to assess how these paradigms impact on clinical nursing practice to identify their benefits and limitations. Based on current research findings and the professional experiences of the nurse-experts, the author was then able to develop a conceptual model that more accurately represented the expert's decision-making process related to pressure ulcer management.

### Clinical Indicators

Current nursing research divides the domain of pressure ulcers into distinct prevention and management paradigms. The identification of those clinical indicators that impact pressure ulcer development and the control of these indicators has been the focus of decades of research yet there is still no standardized risk assessment method that reflects the merging of nursing theory and clinical practice. Of the risk assessment tools that do exist, all are based on two models that continue to be the cornerstone of decision-making and action by clinical nurses [45,55-57,60,66,69]. These are:

1. the Braden Scale for Predicting Pressure Sore Risk (See Appendix B);
2. the Norton Risk Assessment Scale (See Appendix C)[19].

The objective of these risk assessment tools has been to identify high risk patients and to identify the factors that place a patient at-risk. Yet there are two major limitations associated with these tools that have restricted their direct applicability into clinical practice: 1) there are no prevention measures associated with a risk factor and 2) the selection and organization of etiologic factors are inconsistent with the decision processes of clinical domain experts. The lack of a systematic patient risk assessment methodology linking risk

[19] While numerous risk assessment tools exist, only the Norton and Braden Scales have been tested extensively for sensitivity, specificity and inter-rater reliability [45].

factors with appropriate prevention interventions has contributed to the increasing incidence of pressure ulcers [67].

In spite of this increase in pressure ulcers, risk assessment tools continue to be used as guides to clinical practice. Clinical nurse-experts use these tools in three ways: 1) as templates in the design of new risk assessment tools; 2) as an organizational framework for teaching pressure ulcer prevention and management; and 3) as a basis for a consistent language and communication among health care professionals [39,40,44-46,54,55,60]. None of these tools however, model the combination of theoretical and experiential knowledge of the clinical domain expert. Modeling domain expertise therefore, was the second outcome of this work -- the development of a conceptual model that defines the content and hierarchy of decision-making processes of clinical nurses experts in pressure ulcer prevention and management.

As cited earlier, nurses tend to collect large amounts of data that are not always relevant to patient care and the sheer volume of data can impede effective decision-making [32]. This tendency becomes evident when comparing the number and/or definitions of risk factors considered in tools such as the Braden and Norton Scales against the type and amount of data collected and used by clinical nurse-experts. For example, the Braden/Norton Scales differentiate the criteria *Activity* into the following choices: bedfast; chairfast/chairbound; walks occasionally/walks with help; and walks frequently/ambulant. The Braden Scale offers lengthy definitions and includes information for each criteria choice, while the Norton Scale provides none. The criteria used by the nurse-experts in clinical practice was similar to those listed in the Norton/Braden Scales, yet the nurse-experts consider the order and unambiguous definitions as critical components associated with the selection of *Clinical Indicators*.

The collective experiences of the nurse-experts showed that when criteria cannot be applied uniformly to patients, the likelihood of different non-expert nurses selecting inconsistent and/or inappropriate interventions increases. To illustrate, a patient may be bedfast for two reasons: 1) a physical condition such as a coma; or 2) because a patient feels too ill to spend much time being mobile and as a result spends most of a 24 hour period in bed. Labeling a patient *bedfast* for the first reason is unequivocal. Applying *bedfast* to a patient for the second reason however, can become equivocal. One nurse will define the patient as bedfast because it represents their actual level of activity while another will not as the label does not reflect their actual capabilities. Restricting the definition of *Activity* to be representative of how a patient spends the **majority** of their time, irrespective of cause, diminishes the opportunity for misinterpretation of the criteria and therefore, increases the likelihood of appropriate nursing interventions selected and implemented in a more timely manner.

Another example of where data collection becomes too large to be relevant to patient care occurs with the criteria *Mobility*. The Braden and Norton tools differentiate *Mobility* into the choices: *full; slightly limited; very limited*; and *immobile*. This volume and degree of data differentiation is of limited practical clinical value for the nurse planning patient-specific prevention interventions. The data collected through the use of either of these nursing tools always requires further cognitive processing. For example, the relevant patient data the nurse-expert collects when evaluating a patient's *Mobility* status relates to whether a patient is able or unable to make **effective** position changes (See Figure 12). This information is of immediate clinical significance to the nurse-expert and requires no further data collection or analysis before nursing interventions are selected and implemented.

**Ulcer Configuration**

The second branch of the conceptual model describes the decision-making processes related to the assessment of ulcer configurations. Current nursing paradigms such as described in The National Pressure Ulcer Advisory Panel Staging Criteria for Pressure Ulcers (See Appendix D), use a standardized grading or staging classification system that describe the degree of tissue damage observed. There is however, no universally accepted standard for staging a pressure ulcer [45,54]. Considerable and contradictory information exists in defining not only the number of stages and what objective symptoms belong within each stage, but also what constitutes effective nursing management of a pressure ulcer [55,67].

The difficulty associated with the use of a standardized wound staging system presents to nurses is in prescribing a standard treatment for a pressure ulcer when no 'standard' ulcer exists [69]. As any ulcer characteristic can appear within more than one staging definition, it becomes even more difficult for non-experts to identify the appropriate stage and thus, appropriate nursing interventions [55]. The use of staging criteria as a means of ulcer identification therefore, is inappropriate to clinical nursing practice.

A crucial element of treating a pressure ulcer lies not just in the selection of appropriate interventions but also in the consistent application of these interventions by all nurses [39,40,44,55]. When interventions are based on specific patient data, rather than a standardized wound classification system, the likelihood of using effective and appropriate nursing actions is increased [69]. The lack of consistency in application of interventions however, continues to occur in non-expert nursing practice [49,55].

The 1989 Consensus Development Conference on Pressure Ulcers by the National Pressure Ulcer Advisory Panel based their staging system on previous staging models and encourages all health professionals to adopt this model into clinical practice [66]. The NPUAP staging classification model however, suffers the same limitations as the risk assessment tools: 1) treatments are not linked to specific signs and 2) ulcer configuration assessments based on staging criteria are inconsistent with how nurse-experts reason and make decisions.

Another limitation of the NPUAP model is that no information is included to guide the non-expert when the ulcer depth cannot be determined. In a Staging system of wound classification, the nurse (expert and non-expert) is asked to determine the type of skin and/or tissue structures involved. Information on how this is to be accomplished consistently and accurately and without misinterpretation is not included. This results in the potential for misclassification of a pressure ulcer, which impacts on the selection of appropriate treatment interventions. For instance, when either necrotic tissue or exudate are present, accurate assessment of an ulcer becomes at best difficult and at worst impossible to determine. When either of these conditions are present, specific interventions must be performed before identification of a Stage can occur.

According to the nurse-expert consultants, the use of Staging always requires further cognitive processing before an ulcer can be assigned to a stage. Due to the limitations of the NPUAP Staging system, the nurse-experts have evolved their own methods for ulcer classification that also link ulcer characteristics to treatment (Figures 5 - 10). One of the deciding criteria in their assessment methodology is the determination of tissue color (See Figures 7 - 10), which enables the nurse-expert to identify the affected tissue and hence, the wound depth. The nurse-expert's methodology also provides information on situations when tissue depth cannot be determined (See Figure 7). For example, in the case of the presence of eschar (*BLACK*), depth cannot be assessed visually and interventions are required before the *Wound Appearance* can be determined. Once completed, the ulcer configuration assessment is continued.

**Evaluation**

Modeling the domain content and decision processes is a critical precursor to expert system development. Verification and validation products were completed at various stages of this modeling process. These products were used to confirm the completeness and correctness of the knowledge base. As each module of the conceptual model was constructed, the nurse-experts and the knowledge engineer discussed, reviewed, and made modifications as necessary. This process continued until the nurse-experts were convinced their decision-making processes were accurately reflected in the conceptual model.

When experts employed in the construction of the knowledge base are used in its evaluation, their evaluation may be biased [72]. To minimize this bias, a fourth expert nurse-practitioner was enlisted for an evaluation of the final conceptual model contents. Through interviewing, and observation, this nurse-expert described her clinical practice and decision-making processes in the assessment of four patient's at risk for pressure ulcer prevention. These decision-making processes (one patient profile was outlined in Section 3.5), were then compared with the content and processes of the low-level conceptual model (Figures 5 - 16).

The difference detected between the nurse-practitioner and the conceptual model was in the amount of patient data collected in a patient assessment. To illustrate, when a patient's *Activity* status was assessed as *up without help*, the nurse-practitioner concluded there was no risk of pressure ulcer development and would end her assessment. The content of the conceptual model indicates that practitioners continued their assessment until the *Sensory Perception* status was determined. Only if no *Sensory Perception* deficit existed was the *Clinical Indicators* assessment process terminated . With the exception of this one difference, the nurse-practitioner's content and decision-making process associated with the four patient case studies were identical to the content of the conceptual model.

### 4.2.1. Constraints on the Pressure Ulcer Conceptual Model

The aim of the nursing standards or paradigms currently available to nurses is to provide guidance and support for nurse decision-making. Yet none of the researchers appears to have considered or incorporated expertise theory and/or decision modeling in their paradigm designs. There is a need to incorporate the content of pressure ulcer decision-making with the process of this decision-making. The conceptual model presented (See Figures 3 - 16) is a result of the successful merging of research findings and clinical experiences representing the 'knowing what' and 'knowing how' of local nurse-experts. Yet there are limitations associated with this model.

Only nurse-experts associated with the major acute and long-term health care facilities for Vancouver Island were used in the conceptual model construction. While these experts are responsible for a large geographical area that includes eight facilities, they in fact, only represent two distinct hospital societies (the Greater Victoria Hospital Society and Juan de Fuca Hospital Society). To demonstrate the accuracy of this conceptual model across diverse health care institutions, nurse-experts representing other hospitals would be required for a more extensive validation of this model.

The benefits of the expert system to the users, the patients and the health care institution also require evaluation. One method of determining benefits would be to evaluate the expert system's reliability. Quantitative analyses of data generated in clinical trials of a fully developed expert system would have to be conducted to determine not only the extent of the model's consistency and accuracy, but the system's performance and limits of competence. For example, what is the sensitivity, specificity and predictive values of the system's advice? What is the cost of insufficient or excess treatment in human and financial terms? Other aspects of a pressure ulcer prevention and management expert system used in nursing practice that a clinical trial could and should evaluate include: 1) is there a decrease in overall incidence rates of formed ulcers?; 2) is there a decrease in the severity of formed ulcers?; and 3) what is the rate of healing in formed ulcers? Only as questions such as these are answered will the benefits of using computerized decision support become known.

Since expert systems are intended as a type of decision-support for providing problem-specific assistance to non-experts, ideally you want to evaluate the system's effectiveness and acceptability. For any expert system developed, the knowledge engineer must evaluate how effective is it at: 1) solving the domain problem; 2) improving the decision making skill of the nurse; and 3) improving patient outcomes.

As this project was not developed beyond a limited prototype phase, a full evaluation was not possible. What was accomplished however, were validation and verification products that were used throughout for each KE phase to ensure the conceptual model (or the framework of the system) was complete and correct. It was the process of examining and discussing the content of these products , the experts were able to determine and agree that the key domain elements and decision paths were accurate. The final product of this research was a conceptual model that (with further work), could be developed into an expert system that allow for an evaluation of the system's effectiveness and acceptability as the model represents the content and application of pressure ulcer configuration and clinical risk indicator nursing knowledge

## 4.3 Future Work

A goal of nursing research is to improve the quality of patient care delivery. Central to this goal is the challenge of merging research findings with clinical experiences to help inform and direct professional nursing practices [32,33,39]. The paucity of research based guidelines, standards or protocols implemented into nursing practice attests to the slow rate at which nursing has been bridging the gap between research and clinical practice. Yet as the scientific base of nursing knowledge develops and grows, research and continuing education become the *sine qua non* of efficient and effective nursing practice [54]. The impact of expert system design that is based on theoretical knowledge and the experiential knowledge of clinical experts can be assessed and discussed under two headings: research; and clinical nursing care.

**Research**

Clinical nursing experts often work in areas where scientific knowledge lags behind the practical or empirical knowledge, yet quality nursing care must be provided even in the absence of a detailed scientific understanding of a disease. While nursing theory captures much of the detail of how pressure ulcers are explained and understood, they do not provide details of how and when to apply this knowledge in an expert fashion. The advancement of nursing knowledge includes the clarification of how nurses apply clinical knowledge and judgment. The adequate identification of methods aimed at defining nursing expertise is essential to the development and extension of nursing science. Without this, the capture and formalization of clinical expertise in nursing will not be possible.

When nurse experts can articulate their expertise, this knowledge can be formalize and made available to large numbers of non-experts. Researchers must strive to identify, define and explain the cognitive processes involved in nursing practice if theory and research are to be successfully incorporated into clinical nursing practices. The nursing profession therefore, must take a lead role into conducting more research in the nature of clinical nursing expertise. While nursing has lacked a comprehensive and systematic methodology for defining and capturing the content and processes expert decision making, the KE methodology discussed here is a structured and systematic approach for eliciting nursing knowledge and decision making

**Clinical Nursing Care**

As health care funds diminish, demands for accountability are made of all health care professionals. To meet this demand, nurses must increasingly demonstrate how nursing resources are best used by nurses to improve the quality of patient care delivery. When nurses examine their daily practices and critically question their nursing effectiveness, they frequently uncover rituals and traditions that are neither effective nor efficient. Nursing practice guidelines based on the amalgamation of research and expert clinical knowledge has been shown to make a difference to patient outcomes and nurse satisfaction [32,33].

Clinical expertise only comes with time and experience. The use of a model of expert nursing knowledge that is both accurate and **practical** can have a positive impact on nursing and patient care from several perspectives: 1) from a utilization management perspective where nursing knowledge could be employed in clinically and financially more responsible ways; 2) from a clinical excellence perspective where patients are done a disservice when preventable conditions are not prevented but also when preventable conditions worsen; and 3) from a professional development perspective where the individual nurse's own internal knowledge base is being improved with the access and use of expert level knowledge .

This model represents a new and unique way of looking at pressure ulcer prevention and management that is more representative of actual expert clinical practice. This conceptual model not only adds new information to the nursing profession's knowledge base but it is in a format that can be readily usable in a clinical situation. The adoption a model linking decision making and appropriate interventions into clinical nursing practice increases the potential of reducing negative patient outcomes associated with pressure ulcers with a resultant reduction in associated health care costs. Further work in Determining Treatment and Prevention Interventions (See Figure 3) would make increase the practicality and accuracy of the model presented in this research.

## 4.4 Summary

The research question raised was whether an expert system could be designed as a tool to aid non-expert nurses assess and implement pressure ulcer prevention and management strategies. An affirmative answer to this question would be based on the following: can a decision model representative of the nurse-experts decision-making processes be created?; can a knowledge base be written based on this model?; and can the knowledge base contents be verified and validated by the nurse-expert consultants?

The components of the pressure ulcer assessment and management decision model (See Figure 3, p.54) selected for development were the decision-making processes associated with the clinical indicators and ulcer configuration. The treatment and prevention intervention modules were nearly completed but as yet require further work and validation by the nurse-experts. These intervention strategies however, are based on algorithmic rather than heuristic decision-making processes and little time and effort would be required to see these modules to completion.

The two chief accomplishments of this research project have been: 1) a knowledge engineering methodology for capturing nursing knowledge and 2) the creation of a conceptual model representing the decision-making processes associated with the clinical indicators and ulcer configuration characteristics. The KE developed in this research represents an opportunity for the profession to continue the process of clearly defining what clinical nursing knowledge consists of. The conceptual model represents a new nursing paradigm that documents: 1) those clinical indicators predisposing a patient to ulcer formation and 2) the configuration characteristics of a formed pressure ulcer. Based on the products delivered as a result of this research, it is possible to design a pressure ulcer prevention and management expert system for use as a decision support aid for non-expert nurses. The key element in this process however, is in the accurate capture and modeling of the clinical decision making processes

# 5. CONCLUSIONS

In the past, the detail involved in describing how, when and where expertise can or should be applied was picked up by apprentices watching their masters at work. Today, the number of apprentice or novice nurses continues to rise and outnumber the master or nurse expert in the area of pressure ulcer prevention and management, resulting in an increased incidence of pressure ulcers [65-67]. A well constructed expert system can provide the type of knowledge needed by novice nurses to care for pressure ulcers. By building an expert system, the expert is encouraged and guided in verbalizing and documenting their expertise in a format that makes this expertise reproducible and testable by others beyond the expert's immediate environment.

Today, academics and graduate students represent the majority of those building clinical expert systems [79,80]. The point of developing these systems is usually to explore theoretical issues and consequently, the intent is to evaluate the performance of a theoretical model [80]. This type of implementation often neglects user acceptability, system performance, documentation and maintenance issues. When the goal of development is to obtain an academic degree or to test a theoretical model, it is not surprising that the majority of systems fail to become used in the clinical environment as the system is not intended to be fully engineered.

There is a distinction between designing an expert system for the sake of research and to provide a clinically practical decision support tool for non-expert users [80]. If a proposed system is intended to address an actual nursing problem, then the genuine need for the expert system as a solution must be determined. This is accomplished by determining the quality and nature of decisions currently made and the impact errors in clinical judgment currently have on patients. One method of ensuring this occurs is to seek input from those clinical nurses familiar with these issues. This increases the likelihood that the proposed system matches as closely as possible the user's requirements.

Technological or computer advances cannot provide answers to all things. Regardless of the sophistication of the technology, how individuals use or abuse computer systems will remain a limiting factor in a system's facility for improving nursing efficiency and quality of health care delivery. Information technology provides an opportunity to better control nursing practice and activities than previously experienced. Technologies such as expert systems have the capacity for aiding nurses to advance the professions knowledge base at a rate faster than previously known. While an institution may incur initial costs in terms of hardware, software, personnel, supplies and ongoing maintenance, there remains the opportunity for significant strides in the quality of nursing care delivered as well as the development and expansion of the profession's formal knowledge base.

This thesis has introduced an approach to knowledge engineering for eliciting nursing knowledge. The domain of pressure ulcer prevention and management knowledge was selected and then portions of this domain were elicited and represented in a conceptual model. This model was subjected to verification and validation techniques until the nurse-expert consultants were satisfied as to the accuracy and completeness of the model.

The Clinical Indicators for pressure ulcers was used as the basis of an implementation model constructed as a decision table. This table was reviewed and revised by the knowledge engineer and the nurse-experts, then incorporated onto VPExpert's expert system shell in the form of **IF-THEN** statements. While the knowledge base was verified as accurate, the nurse-experts were unable to validate the system output until the Prevention and Treatment Interventions could be completed and added to the knowledge base. Future work therefore, will focus on extending the implementation model to include the ulcer configuration characteristics and all interventions and then expanding the knowledge base to reflect these extensions.

The weaknesses of this research are in two areas: 1) user acceptability has not been tested and 2) defining and linking the interventions to specific decision making processes has not been completed. The strengths of this research are that the conceptual model; 1) is based on clinical practice and expertise and 2) identifies where nursing practice and research diverges and links together to form a more accurate and practical model for clinical nursing.

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# APPENDICES

## Appendix A

An accurate calculation of pressure ulcer (PU) cost requires knowledge of the number of acute care admissions to a health care facility yet, other than from the GVHS, this information is unavailable. The estimated costs presented are based on the number of GVHS admissions (excluding maternity, pediatrics and psychiatric beds) extrapolated to the numbers of acute care beds in the rest of British Columbia and Canada.

There are three sets of calculations presented below: 1) estimated local costs; 2) estimated provincial costs; and 3) estimated national costs.

| | GVHS | | BC | | CANADA | |
|---|---|---|---|---|---|---|
| Incidence Rate | 3% | 14% | 3% | 14% | 3% | 14% |
| # Annual Admissions | 33444 | 33444 | | | | |
| # Acute Care Beds | 1659 | 1659 | 9682 | 9682 | 91449 | 91449 |
| Cost per Bed per Day | $1,026 | $1,026 | $1,026 | $1,026 | $1,026 | $1,026 |
| Average Increase in Length of Hospital Stay | 10 | 10 | 10 | 10 | 10 | 10 |
| Percent of PU Preventable | 50% | 50% | 50% | 50% | 50% | 50% |
| **Costs of PU** | **$5 M** | **$24 M** | **$30 M** | **$140 M** | **$284 M** | **$1,324 M** |

These approximate costs associated with pressure ulcer management require several assumptions be made explicit:

- the US pressure ulcer rates of 3 - 14%[20] for acute care admissions represent the incidence rates of pressure ulcer formation in Canadian acute care settings [45];
- maternity, pediatric and psychiatric beds are not included in the numbers of acute care beds;
- the cost of an acute care bed at the GVHS ($1026.00) can be extrapolated to the provincial and national level;
- the average length of stay for a patient who has developed a pressure ulcer is 10 days over the initial medical reason for hospital admission [61,67,69];
- a 50% reduction in pressure ulcers is achievable [45].

[20] This figure excludes pediatric, psychiatric and maternity beds. For these calculations however, the number of maternity beds cannot be excluded from the total number of acute care beds for the national and provincial costs. The Canadian Hospital Association does not separate maternity beds in their calculation of numbers of General beds available.

# Appendix B

The Braden Scale for Predicting Pressure Ulcer Risk

Patient's Name____________Evaluator's Name____________ Date of Assessment

| | | | | | |
|---|---|---|---|---|---|
| **SENSORY PERCEPTION**<br><br>ability to respond meaningfully to pressure-related discomfort | **1. Completely Limited**<br>Unresponsive (does not moan, flinch, or grasp) to painful stimuli, due to diminished level of consciousness or sedation.<br>**OR**<br>limited ability to feel pain over most of body surface. | **2. Very Limited**<br>Responds only to painful stimuli. Cannot communicate discomfort except by moaning or restlessness.<br>**OR**<br>has a sensory impairment which limits the ability to feel pain or discomfort over 1/2 of body. | **3. Slightly Limited**<br>Responds to verbal commands, but cannot always communicate discomfort or need to be turned.<br>**OR**<br>has some sensory impairment which limits ability to feel pain or discomfort in 1 or 2 extremities. | **4. No Impairment**<br>Responds to verbal commands. Has no sensory deficit which would limit ability to feel or voice pain or discomfort. | |
| **MOISTURE**<br><br>degree to which skin is exposed to moisture | **1. Constantly Moist**<br>Skin is kept moist almost constantly by perspiration, urine, etc. Dampness is detected every time patient is mover or turned | **2. Very Moist**<br>Skin is moist often, but not always moist. Linen must be changed at least once a shift. | **3. Occasionally Moist**<br>Skin is occasionally moist, requiring an extra linen change approximately once a day | **4. Rarely Moist**<br>Skin is usually dry, linen only requires changing at routine intervals. | |
| **ACTIVITY**<br><br>degree of physical activity | **1. Bedfast**<br>Confined to bed | **2. Chairfast**<br>Ability to walk severely limited or non-existent. Cannot bear own weight and/or must be assisted into chair or wheelchair. | **3. Walks Occasionally**<br>walks occasionally during day, but for very short distances, with or without assistance. Spends majority of each shift in bed or chair. | **4. Walks Frequently**<br>Walks outside the room at least twice a day and inside room at least once every 2 hours during waking hours | |
| **MOBILITY**<br><br>ability to change and control body position | **1. Completely Immobile**<br>Does not make even slight changes in body or extremities position without assistance. | **2. Very Limited**<br>Makes occasional slight changes in body or extremity position but unable to make frequent or significant changes independently. | **3. Slightly Limited**<br>Makes frequent though slight changes in body or extremity position independently. | **4. No Limitations**<br>Makes major and frequent changes in position without assistance | |
| **NUTRITION**<br><br>*usual* food intake pattern | **1. Very Poor**<br>Never eats a complete meal. Rarely eats more than 1/3 of any food offered. Eats 2 servings or less of protein (meat or dairy products) per day. Takes fluids poorly. Does not take a liquid dietary supplement.<br>**OR**<br>is NPO and/or maintained on clear liquids or IV's for more than 5 days. | **2. Probably Inadequate**<br>Rarely eats a complete meal and generally eats only about 1/2 of any food offered. Protein intake includes only 3 servings of meat or dairy products per day. Occasionally will take a dietary supplement.<br>OR<br>receives less than optimum amount of liquid diet or tube feeding. | **3. Adequate**<br>Eats over half of most meals. Eats a total of 4 servings of protein (meat, dairy products) each day. Occasionally will refuse a meal but will usually take a supplement if offered.<br>OR<br>is on tube feeding or TPN regimen which probably meets most of nutritional needs | **4. Excellent**<br>Eats most of every meal. Never refuses a meal. Usually eats a total of 4 or more servings of meat and dairy products. Occasionally eats between meals. Does not require supplementation. | |
| **FRICTION AND SHEAR** | **1. Problem**<br>Requires moderate to maximum assistance in moving. Complete lifting without sliding against sheets is impossible. Frequently slides down in bed or chair, requiring frequent repositioning with maximum assistance. Spasticity, contractures or agitation leads to almost constant friction. | **2. Potential Problem**<br>Moves feebly or requires minimum assistance. During a move skin probably slides to some extent against sheets, chair, restraints, or other devices. Maintains relatively good position in chair or bed most of the time but occasionally slides down | **3. No Apparent Problem**<br>Moves in bed and in chair independently and has sufficient muscle strength to lift up completely during move. Maintains good position in bed or chair at all times. | | |
| | | | | **TOTAL SCORE** | |

[56, p.45]

# Appendix C

The Norton Risk Assessment Scale

| A<br>Physical Condition | B<br>Mental State | C<br>Activity | D<br>Mobility | E<br>Incontinence | TOTAL SCORE |
|---|---|---|---|---|---|
| 4 Good | 4 Alert | 4 Ambulant | 4 Full | 4 Not | |
| 3 Fair | 3 Apathetic | 3 Walks with Help | 3 Slightly Limited | 3 Occasional | |
| 2 Poor | 2 confused | 2 Chairbound | 2 Very Limited | 2 Usually Urine | |
| 1 Bad | 1 Stupor | 1 Bedrest | 1 Immobile | 1 Double Incontinence | |

Norton Plus Scale
(For determining high risk for pressure sores)

| **Check ONLY if yes** | **YES** |
|---|---|
| Diagnosis of diabetes | ____ |
| Diagnosis of hypertension | ____ |
| Hematocrit (M) <41% (F) <36% | ____ |
| Hemoglobin (M) <14 g/dl] (F) <12 g/dl | ____ |
| Albumin level <3.3 g/dl | ____ |
| Febrile >99.6$^{o}$ F | ____ |
| 5 or more medications | ____ |
| Changes in mental status to confused, lethargic within 24 hrs. | ____ |
| **TOTAL Number of Check marks** | |
| Norton Scale Score | ____ |
| Minus total from above | ____ |
| Norton Plus Score | ____ |

[55, p.269]

# Appendix D

The National Pressure Ulcer Advisory Panel Staging Criteria for Pressure Ulcers

| STAGE | DESCRIPTION |
| --- | --- |
| Stage I | Non-blanchable erythema of intact skin; the heralding lesion of skin ulceration. Note: Reactive hyperemia can normally be expected to be present for one-half to three-fourths as long as the pressure occluded blood flow to the area; it should not be confused with a Stage I pressure ulcer |
| Stage II | Partial thickness skin loss involving epidermis and/or dermis. The ulcer is superficial and presents clinically as an abrasion, blister or shallow crater |
| Stage III | Full thickness skin loss involving damage or necrosis of subcutaneous tissue that may extend down to, but not through, underlying fascia. The ulcer presents clinically as a deep crater with or without undermining of adjacent tissue. |
| Stage IV | Full thickness skin loss with extensive destruction, tissue necrosis or damage to muscle, bone or supporting structures (for example, tendon or joint capsule). Note: Undermining and sinus tracts may also be associated with Stage IV pressure ulcers |

[66, p.1]

# Appendix E

| | ACTIVITY | MOBILITY | SENSORY PERCEPTION | MOISTURE | FOOD INTAKE | HYDRATION | WEIGHT |
|---|---|---|---|---|---|---|---|
| 1 | bedfast | no_shift | yes | always | inadequate | y | ideal/over |
| 2 | bedfast | no_shift | yes | always | inadequate | y | under |
| 3 | bedfast | no_shift | yes | always | inadequate | n | ideal/over |
| 4 | bedfast | no_shift | yes | always | inadequate | n | under |
| 5 | bedfast | no_shift | yes | always | adequate | yes_no | ideal/over |
| 6 | bedfast | no_shift | yes | always | adequate | yes_no | under |
| 7 | bedfast | no_shift | yes | sometimes | inadequate | y | ideal/over |
| 8 | bedfast | no_shift | yes | sometimes | inadequate | y | under |
| 9 | bedfast | no_shift | yes | sometimes | inadequate | n | ideal/over |
| 10 | bedfast | no_shift | yes | sometimes | inadequate | n | under |
| 11 | bedfast | no_shift | yes | sometimes | adequate | yes_no | ideal/over |
| 12 | bedfast | no_shift | yes | sometimes | adequate | yes_no | under |
| 13 | bedfast | no_shift | yes | never | inadequate | y | ideal/over |
| 14 | bedfast | no_shift | yes | never | inadequate | y | under |
| 15 | bedfast | no_shift | yes | never | inadequate | n | ideal/over |
| 16 | bedfast | no_shift | yes | never | inadequate | n | under |
| 17 | bedfast | no_shift | yes | never | adequate | yes_no | ideal/over |
| 18 | bedfast | no_shift | yes | never | adequate | yes_no | under |
| 19 | bedfast | no_shift | no | always | inadequate | y | ideal/over |
| 20 | bedfast | no_shift | no | always | inadequate | y | under |
| 21 | bedfast | no_shift | no | always | inadequate | n | ideal/over |
| 22 | bedfast | no_shift | no | always | inadequate | n | under |
| 23 | bedfast | no_shift | no | always | adequate | yes_no | ideal/over |
| 24 | bedfast | no_shift | no | always | adequate | yes_no | under |
| 25 | bedfast | no_shift | no | sometimes | inadequate | y | ideal/over |
| 26 | bedfast | no_shift | no | sometimes | inadequate | y | under |
| 27 | bedfast | no_shift | no | sometimes | inadequate | n | ideal/over |
| 28 | bedfast | no_shift | no | sometimes | inadequate | n | under |
| 29 | bedfast | no_shift | no | sometimes | adequate | yes_no | ideal/over |
| 30 | bedfast | no_shift | no | sometimes | adequate | yes_no | under |
| 31 | bedfast | no_shift | no | never | inadequate | y | ideal/over |
| 32 | bedfast | no_shift | no | never | inadequate | y | under |
| 33 | bedfast | no_shift | no | never | inadequate | n | ideal/over |
| 34 | bedfast | no_shift | no | never | inadequate | n | under |
| 35 | bedfast | no_shift | no | never | adequate | yes_no | ideal/over |
| 36 | bedfast | no_shift | no | never | adequate | yes_no | under |
| 37 | bedfast | minor | yes | always | inadequate | y | ideal/over |
| 38 | bedfast | minor | yes | always | inadequate | y | under |
| 39 | bedfast | minor | yes | always | inadequate | n | ideal/over |
| 40 | bedfast | minor | yes | always | inadequate | n | under |
| 41 | bedfast | minor | yes | always | adequate | yes_no | ideal/over |
| 42 | bedfast | minor | yes | always | adequate | yes_no | under |

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Peterson, G.M., Fisher, P.D., (1993). An expert system for pressure ulcers: A work in progress. *Canadian Conference on Electrical and Computer Engineering* pp.973-976.

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Title of Thesis: EXPERT SYSTEM DEVELOPMENT IN NURSING: Knowledge Engineering Methods for a Pressure Ulcer Expert System for Clinical Nurses

Aut[redacted]

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September 1/95

(Date)