9 Patient Care

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INTRODUCTION

Up to 1999, when the seminal report *To Err Is Human* was announced, most health care professionals were unaware of the significance of their own mistakes, because there was little or no supporting infrastructure to report and track adverse events and medical errors [1–3]. Since then, a wide range of research has been conducted to identify risks to patients and to prevent medical errors. Although the research has significantly enhanced patient safety, adverse events still occur occasionally as surgical procedures become more complex through the development of advanced medical technologies and our extended life expectancy. According to a report by Pronovost et al., the most common errors were related to medication (42%), incorrect and incomplete delivery of care (20%), and equipment failure (15%) [4]. For example, medications may be ordered incorrectly, due to a misinterpretation of a doctor's handwriting on a prescription; medical errors may be attributed to a failure in administering the correct dosage during the appropriate time frame; incorrect and incomplete surgeries may be performed due to retained foreign bodies, wrong-site operations, mismatched organ transplants, and incompatible blood transfusions; and equipment failure may occur when the required instruments are arranged incorrectly, sterilized improperly, or mismatched. These errors seem inevitable when we consider medical practices in which complicated and critical decisions are necessitated, frequently with limited and conflicting information [5,6]. In addition to this, ensuring patient safety becomes even more challenging when a patient is transferred from one institution to another or from one surgeon to another. These medical hand-offs happen frequently both in the theater of war and in civilian medical practices [7–10].

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The OR (operating room) is particularly susceptible to medical error, due to its complex and multidisciplinary nature. Communication among team members becomes more difficult, as shown in a report stating that over 70% of sentinel events are associated with teamwork and communication in obstetric critical care [11].[†] This is also indicated by a study reporting that even the level of teamwork in the OR is perceived differently by team members such as surgeons and nurses [12]. Medical errors rooted in miscommunication generally occur when team members happen to have different viewpoints [13]. Doctors may change orders without adequately communicating with nursing staffs; incorrect patient information may be passed through different medical teams; team members' responsibilities may be delegated ineffectively and their roles may not be clarified in detail; or some team members may have inaccurate assumptions of the knowledge and skills of other members. Although a wide variety of factors contribute to the high risk of medical errors in the OR, poor and ineffective communication is a major contributing factor [14]. In addition, the Joint Commission on Accreditation of Healthcare Organizations has identified communication breakdown as a leading cause of medical errors [15]. There is a strong consensus that communication in the OR is essential to patient safety and quality care [12,16,17]. Up until now, however, findings are still very limited and more research is necessary. To that end, we provide a computational methodology to help improve communication among medical team members in the OR by analyzing gaps while inferring intent of the team members. We assume a system that monitors the OR team members continuously and aims to assist their understanding of dynamic situations/environments and of their co-workers in order to enhance patient safety and the quality of medical care.

Communication and information sharing are essential to patient safety but can easily break down in the OR with people of various skill levels and ranks cooperating with each other and interacting dynamically, allowing unintended events to occur frequently [18–20]. For better team communication, it is ideal that all the OR team members perform their roles and tasks with a continual understanding of the surrounding dynamic situations. To improve patient safety, all the OR team members should reconsider current decisions and reverify the surgical procedures to be taken when a significant discrepancy is observed among their decision-making processes.

In our research, we model how the OR team members understand the situation through **intent inferencing**, where a person's intent is defined as a combination of goals and supporting actions and plans, and is inferred based

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[†] Sentinel event: an unexpected occurrence involving death or serious physical or psychological injury, or any process variation for which a recurrence would carry a significant chance of a serious adverse outcome (http://www.jointcommission.org/sentinelevents/).

on probabilistic reasoning. The **team intent** is derived from the intent of individual care team members. The **gap** value is then computed by comparing the likelihoods of possible situations in each member's intent inferencing. For example, a situation involving all care team members and having a high gap value can be interpreted as a medical situation highly vulnerable to medical errors. A person's intent is shaped by his or her perceptions, knowledge, experience, and awareness of environment, just to name a few factors. When each person's intent is embodied by his or her understanding of other team members, the information available may be incomplete and/or inaccurate and should be addressed appropriately when modeling individual reasoning processes. **Bayesian knowledge bases** (BKBs) form the basis for modeling and simulating the OR team members' decision making [21]. By integrating the intentions and beliefs inferred from individual decision-making processes, we identify the discrepancy between intentions and beliefs among the OR team members and use it as an indicator to detect potential medical errors. Although modeling and simulating individual reasoning is a complex and challenging task, by employing the formalism of BKBs, we can handle issues of uncertainty and incompleteness as well as reduce the computational costs required in the reasoning processes.

We begin our discussion with a section on *related work*, providing some fundamental background for our research. In our discussion on *team performance*, we introduce our gap analysis procedure and how it can be applied in our domain. Then we provide our current cognitive framework for *surgical intent modeling* and its theoretical foundation of BKBs. Next, in our description of an *empirical study*, we present some real-world medical cases containing errors and provide empirical results for validation. Finally, we provide our conclusion and directions for future research.

RELATED WORK

Communication breakdown has continued to be an issue in medical practice. Although a considerable amount of literature has been published to address the issue, we focus on research devoted to improving communication among medical team members. We classify the major research thrusts into three categories: training, checklisting, and intent inferencing.

Training medical care members to enhance patient safety has a long history of research and implementation. In a paper by Awad et al., a special training session, which was based on crew resource management principles, was offered to surgical teams, and the impact of this training was examined by a communication survey collected over several months [22]. The study focused on training OR team members to brief a case before the operation, for the purpose of improving communication. The results of this implementation have been investigated in dedicated hospitals and have shown significant improvement of medical care members' awareness and understanding of the procedures to be performed. Furthermore, the complexity and the dynamics of the OR have been known to parallel those of the aviation environment. Many medical team training systems have employed the principles of aviation crew maneuver training and have shown meaningful improvement [23].

Checklisting is another methodology adapted from aviation crew training principles used to reduce medical errors. The key idea behind the checklist is to standardize processes and to aid the memory of the OR team members. Since this implementation has shown a strong tendency to reduce medical errors, it is currently in very common use in the OR. Among a number of variations in checklist design, the two most popular forms are the to-do list and the challenge–verification–response. The *to-do list* contributes as a systematic way of performing medical procedures, while the *challenge–verification–response* serves as a tool to enhance communication among those involved in the same procedure, such that one party initiates some items from the checklist while another party completes the items [24]. Despite the apparent benefits of the checklist, some medical errors still occur and result in catastrophic outcomes. These causes stem from various sources, many of which are related to poor physician compliance. Some medical care members recite the procedure from memory, not from the checklist; they skip reading the checklist, which would have verified the other party's completeness; some essential items are not included in the checklist, and so on.

Intent inferencing is one of the most advanced techniques dedicated to promoting patient safety because it employs the reasoning tools from artificial intelligence. The research activities include many types of team cooperative tasks, such as central control rooms of power plants, cockpits in aircraft, and medical care members in surgical rooms. In a study by Kanno et al., a two-person team operating a plant control system was simulated by detecting conflict within the team members' intentions [25]. Individual intention was inferred by applying keyhole plan recognition, which searches for a combination of individual mental components with given observables. In addition, there have been multiple studies to maintain quality care by applying computational reasoning and planning, such as ABVAB [26], SPHINX [27], and TraumAID [28]. Our study is in the same line of research. However, we integrate gap analysis to identify potential risks of medical errors and enhance reasoning processes with intent inferencing.

TEAM PERFORMANCE

In the OR, surgery is delivered by several medical professionals, including surgeons, anesthesiologists, and nurses. Medical procedures performed in the

OR are vulnerable to medical errors due to the complexity of surrounding circumstances, where a wide variety of people, medical equipment, activities, and events interact dynamically. Although communication is critical to promote patient safety, it can easily fall apart among medical professionals working as a team in the OR. In this section we address team intent and how the gap is obtained and interpreted in our research to increase situational understanding of team members.

Team Intent

A team is a group of individuals working to achieve common goals. As individual intent leads to a course of actions, team intent leads to the collective actions of team members to achieve common goals. In addition, when team members are better aware of other members' intentions, the team intent can be accomplished in a more effective and efficient manner. High-quality patient care, supposedly a common goal among individual team members, can be better accomplished by enhancing the team intent, which is defined as the collective intent of all team members. However, the intents of the individual team member are not always in accord, often resulting in medical errors. Despite the consensus on the significance of team intent, only a few studies to date have been conducted to address this issue [25]. While existing research concentrates on team intent inference based on a concept of "we-intention," a word coined by Tuomela to represent a set of individual intentions and mutual belief, to simulate a plant controller operated by a two-person team, we focus on quantifying and measuring the level of conflict in teams composed of more than two persons in order to improve patient safety in medical practice [29]. To realize this, we derive team intent from individual intent models and propose a method to quantify team intent by comparing individual intent models. In our understanding, the team intent is time dependent and can either deteriorate or develop, depending on the status of the team members. For example, the team intent may deteriorate when the members of the team perform incorrect procedures or are distracted for personal reasons, such as fatigue or a tragic experience. Analyzing the discrepancy among individuals is a critical step in improving both team members' situational awareness and the team's potential in performing medical procedures and in improving patient safety.

Medical errors are often attributed to the medical care members, especially when they misunderstand the patient, their co-workers, or the surrounding medical situations. For example, a wrong dose of medication may be administered when a nurse misunderstands a doctor's order or the patient's condition. A wrong-site operation can occur when a surgeon is disoriented anatomically by medical images (e.g., MRI or CT) or the nurse prepares the wrong site for operation (e.g., by mistakenly confirming the patient's tattoo as a surgical marking [30]. A retained foreign body occurs when medical care team members leave a peice of operating equipment inside a patient's body when closing an incision. Although anyone can make a mistake, co-workers have the potential to monitor and fix a mistake. Therefore, we would anticipate that a team with more care members would have a better chance of to avoiding medical errors when individual team members know their own responsibilities as well as those of the other team members [23]. However, communication easily breaks down in practice, due to the care members' incomplete and inaccurate understanding of their surrounding situations. Therefore, to improve patient care it is essential to enhance the medical care members' understanding and awareness of their environment.

Gaps Among OR Team Members

A medical situation is composed of medical care members and all necessary equipment. Medical errors are brought about when these components do not function appropriately. A gap is associated with a situation instantiated by these complex components. A large gap suggests that the corresponding situation is vulnerable to medical errors due to discrepancies in individual intents associated with the team. In our research, we consider possible situations from the perspectives of both the team and the individual. To analyze gaps among medical care members, we compute a gap value for a team in a certain situation and use it as a safety measure of the team while performing medical procedures:

$$g(x) = \sum_{i=1}^{n} \sum_{\substack{j=1, \\ i \neq j}}^{n} \mathrm{diff}(\mathrm{ind}(i) - \mathrm{ind}(j)) \tag{9.1}$$

where $g(x)$ represents the gap value of team x in an arbitrary situation composed by n individuals, and $\mathrm{ind}(i)$ denotes the world of an individual i in the same situation. The world of an individual means a common situation as interpreted by that person. Therefore, we can quantify the level of consensus among all members of team x. The gap value computed can be interpreted in various ways, depending on how the individual world is described. With respect to surgical intent modeling, we interpret the gap value as a relative measure of discrepancy among team members in performing medical procedures. Since our intent model is based on probability theory, all individual worlds are represented as the likelihoods of combinations of random variables, and the gap value is obtained by summing the difference of all posterior probabilities obtained from individual intent inferencing. Due to the nature of probability theory, comparing the likelihood of different team intent models may not be meaningful in general. However, we can assume that team x is safer than team y in performing a surgical procedure if $\text{gap}(x) < \text{gap}(y)$, as long as both teams are composed of the same members. Thus, the key difference between the two teams is the team members' intent in performing the medical procedure. For example, when two surgeons cooperate to perform a medical procedure, they need to coordinate with each other when performing their medical actions. Although their actions are different, each has his or her own expectations (beliefs) of the other surgeon. This is also true for other medical care members, such as the anesthesiologist and the nurse, when more care members are involved in performing the same medical procedure. If there is a gap between their intentions and beliefs, this may indicate a potential risk of errors. This may be caused by some care members' lack of experience and knowledge, the distractions they may experience due to fatigue, or the complexity of the procedure.

SURGICAL INTENT INFERENCING

The individual's intent is a psychological concept and can be understood in various ways [31]. In our work, a surgeon's intent is inferred from his or here course of actions and perceptions of the environment. To make this feasible, we need a computational methodology to appropriately represent each person's knowledge and perceptions. We employed Bayesian knowledge bases, a probabilistic knowledge representation, to represent information available in the OR, which is frequently incomplete and uncertain (e.g., information in trauma cases, such as allergies, preexisting conditions, and family history, can often be incomplete in nature because these types of cases emerge rapidly) [32]. Through belief revision with BKBs, we simulate the reasoning processes of health care professionals. In this section we review the basic theory and reasoning processes of BKBs to derive our approach to surgical intent inferencing.

Bayesian Knowledge Bases

Bayesian knowledge bases (BKBs) subsume bayesian networks (BNs) and are represented through directed graphs embracing the causal relationship between pieces of knowledge [33]. Similar to BNs, both graph and probability theories form the theoretical basis for BKBs. A directed graph representation provides a formal and visual expression of causality among pieces of knowledge enclosed, while probability theory guarantees the semantic soundness in decision making under uncertainty and inaccuracy [34]. However, unlike BNs, the BKBs consider partial independence among knowledge pieces and

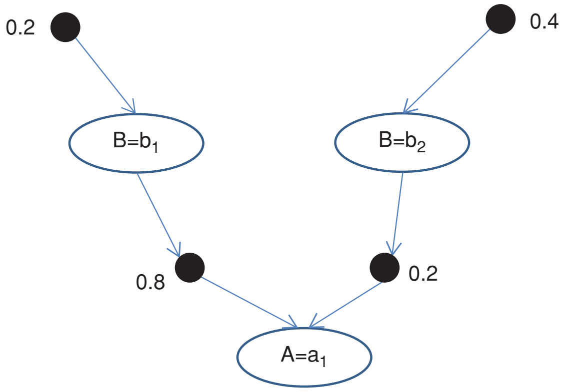


FIGURE 9.1 BKB fragment.

are capable of integrating incompleteness and uncertainty in decision making [32,35]. The nodes of a BKB represent states of random variables, while the arcs denote the causal relationships among the random variables. In particular, the nodes are classified into two types: I-nodes and S-nodes. In an example of small BKBs, as shown in Figure 9.1, the I-nodes, white ovals in the figure, store knowledge to be represented with two random variables, A and B. The dependencies between I-nodes are encoded by S-nodes, while the attached conditional probability indicates the likelihood of the child I-node occurring given that a parent I-node is observed. Consequently, a piece of the knowledge enclosed in the BKB, which can be phrased as $A = a_1$, will occur with an 80% chance when $B = b_1$. In this simple and expressive manner, knowledge can be represented through BKBs.

In general, BNs require a separate conditional probability table containing all possible states of connected random variables, while BKBs focus on partial independence among knowledge. Therefore, BKBs do not require complete knowledge and are capable of reducing complexity when interpreting the knowledge under consideration [36]. Reasoning in BKBs can be implemented in two ways: belief updating and belief revision. Both are based on the dependencies among pieces of knowledge contained, evidence observed prior to the reasoning, and the chain rule:

$$P(X_1, X_2, X_3, \ldots, X_n) = \prod_{i}^{n} P(X_i|\text{parents}(X_i)) \tag{9.2}$$

In *belief updating*, the focus is on updating knowledge by computing the posterior probability of any single I-node using Bayes' theorem. In *belief revision*, the most probable world of random variables is derived by computing and comparing joint probabilities of all possible worlds of random variables. Therefore, we can obtain alternative explanations through belief revision [37].

Algorithms performing these BKB **reasoning processes** have been discussed in detail [36,38]. Consequently, the probabilities of the world obtained in belief revision may become extremely small as the amount of knowledge contained increases. This needs to be interpreted reasonably since the most probable world obtained is one possible explanation that best supports the evidence provided. Naturally, this is only valid regarding the knowledge under consideration. To integrate and aggregate massive knowledge pieces, a fusion algorithm has been developed [39].

Intent Inferencing

Research on intent inferencing has been studied over several decades to represent and understand human decision-making processes and behaviors. *Intent* is an explanation of people's actions and is defined as a combination of the goals that are being pursued, the support for the goals, and the plans to achieve them [40]. To represent human intent through computations, we have designed a system that contains these components and is capable of reasoning through them. Previously, it was applied to adversary intent inferencing on the battlefield, and now we incorporate them for surgical intent inferencing [41–43]. Similar to the adversarial intent inferencing, we integrate components of intent into the structure of BKBs [41]. The knowledge relevant to human intent is categorized into four types: axioms, beliefs, goals, and actions. *Axioms* denote a person's knowledge about himself or herself, whereas *beliefs* denote a person's knowledge about others (including other people and the surrounding environments). *Goals* are used to represent the results that a person wants to achieve. People's actions to be taken to achieve their goals are encoded through *actions*. Figure 9.2 shows these four components arranged

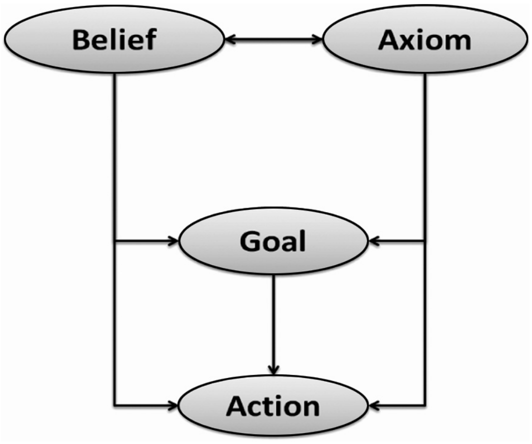


FIGURE 9.2 Hierarchy of interaction between four types of nodes in intent models.

in a hierarchical structure, which is recommended to organize correctly and to categorize knowledge when designing BKBs for intent inferencing.

An intent model is composed of a person's knowledge about himself and others and is based on his observations and perceptions. Naturally, the person's knowledge may not be consistent with that of others or even with the world as it is. Therefore, when a group of intent models are collected to compose the team intent, the discrepancies among them are somewhat natural. However, if these individuals undertake their roles under a certain common goal, the discrepancies can be significant, such as the aforementioned potential risk of errors in medical practices.

Surgical Decision Making

According to patient symptoms, the surgeon diagnoses the patient disease. In addition, the patient's vital condition is involved in the surgeon's decision making. The surgeon's decision making is modeled through five major components, as shown in Figure 9.3. The surgeon diagnoses and determines a potential medical procedure based on patient condition, history, and profile. Based on their personal competence, surgeons confirm a procedure to be taken and then determine a course of action to fulfill the objectives of that procedure.

As shown in Figure 9.4, in the information associated with the patient's disease, the patient's surgical history, and the patient's family history or genetic information can be included while building a BKB for an individual surgeon. For example, (B)Condition_65105 is inferred from patient's vital signs such as pulse rate, respiration rate, and body temperature. When the patient has vital signs within the normal range, a surgeon can choose an

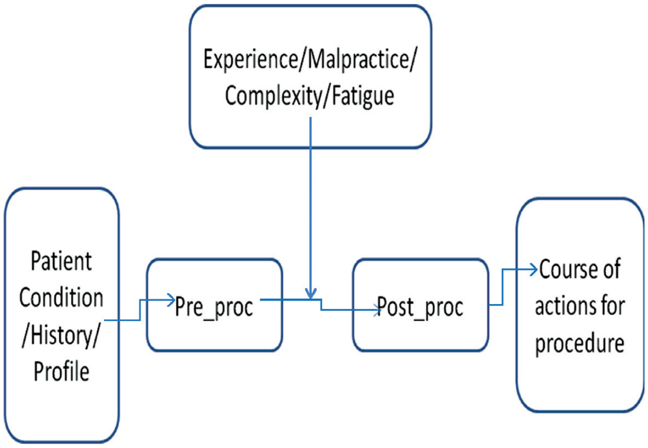


FIGURE 9.3 Skeleton of surgical intent model.

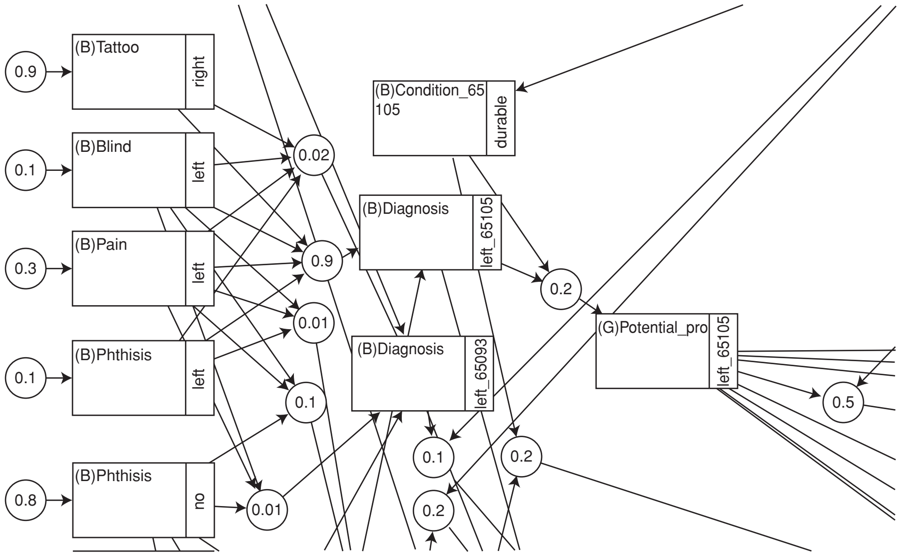


FIGURE 9.4 Patient condition/history/profile.

appropriate procedure. However, if the patient has vital signs that are outside the normal range, a surgeon needs to take an alternative approach for ensuring patient safety. Therefore, it is recommended that an alternative procedure with lower complexity or risk in modeling an individual surgeon's decision making be addressed. Although a surgeon prefers a certain procedure due to her own specialty in general, it is highly recommended that an alternative approach be consided for patient safety, especially for a patient with comorbidities. By linking alternative procedures systematically, an individual intent model can assist a real surgeon effectively since it is possible to build a model to hold more knowledge than a real surgeon can have. In Figure 9.4, two alternative procedures, such as enucleation (65105) and evisceration (65093), are considered [44].

Figure 9.5 shows how personal competence is inferred in the surgeon's decision-making process. This component is composed of various contributing factors: e*xperience* associated with the procedure, *malpractice* in the past, *complexity* of the procedure, and *fatigue*. These factors are embedded in an individual surgeon's BKB to simulate how a surgeon's decision can be changed by these factors. The information can be derived from the quality of medical school, the postgraduate medical training period, the distribution of procedures the surgeon has performed previously, and the surgeon's recent daily schedule. After a care member predetermines his medical procedure (i.e., pre_proc in Figure 9.3) to perform based on the patient information, he may keep his previous decision or change the procedure, depending on his

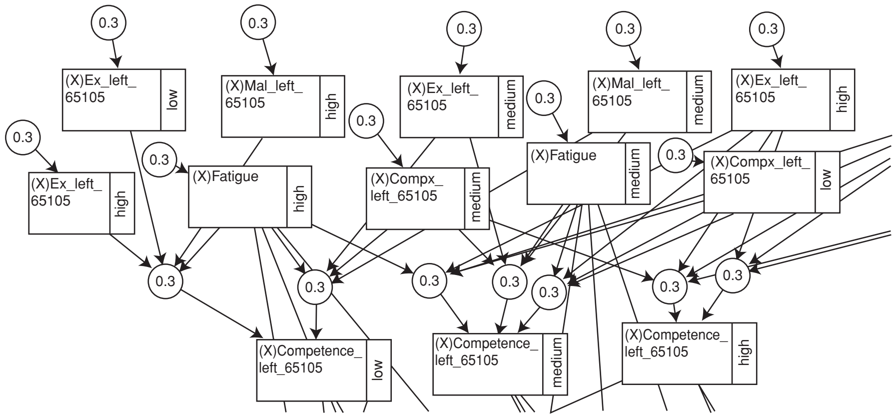


FIGURE 9.5 Experience/malpractice/complexity/fatigue.

personal competence. The background information about the surgeon herself is encoded as *axioms*, represented as (X) in BKBs. Through inferring personal competence from the background information, a potential risk when a highly experienced surgeon becomes very fatigued can be captured. For example, a surgeon with high experience and low malpractice can have a lower ("medium") competence level when she becomes highly fatigued than when she is not fatigued at all. Other OR team members' personal competences are inferred in the same way, but can be specified differently, depending on their specialties in performing medical procedures.

Once the surgeon confirms the procedure to be performed, a course of action is determined. The order of actions can be important, although some actions are reversible [45]. Many patients in the OR have life-threatening injuries or illnesses, and it is important that a surgeon takes the correct action at the appropriate time to ensure patient safety. The previous actions completed by the surgeon and by the other team members need to be considered to correctly determine the next action to be taken. To simulate dynamically, the status of the OR should be monitored continuously, and the information obtained needs to be placed into consideration. According to all the information provided, the most probable action to be taken can be predicted through belief revision of BKBs. Figure 9.6 shows a part of an ophthalmologist's BKB built for our simulation, representing a *course of actions for procedure*. This part can be delineated differently depending on other OR team members' roles and tasks in performing medical procedures as a team.

EMPIRICAL STUDY

To demonstrate the practical aspects of our surgical intent inferencing, we built BKBs representing medical professionals and conducted experiments

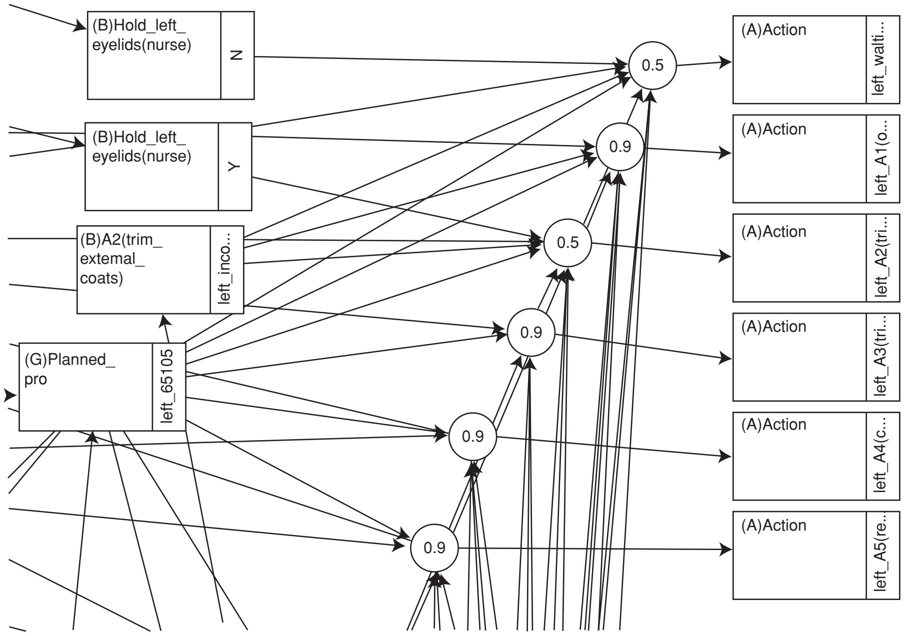
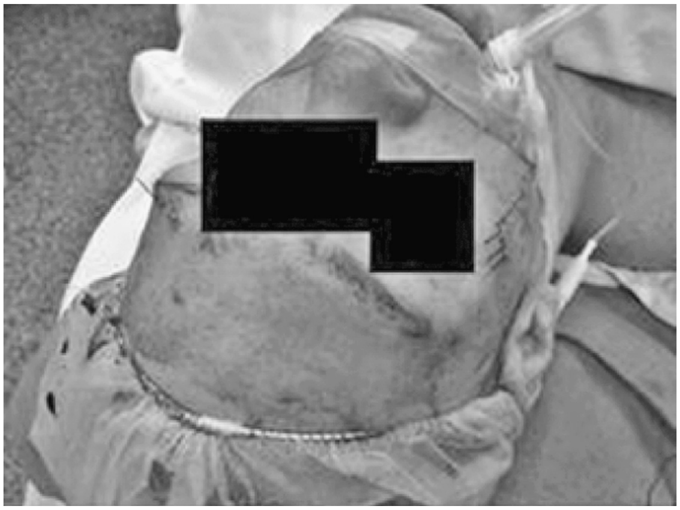


FIGURE 9.6 Course of actions for procedure.

to validate their modeling capability. Previously, we simulated a "hand-off" case of a woman having a breast pain as an example of an adverse event [21]. Communication breakdown between general and plastic surgeons as it pertained to patient hand-off was clearly identified through our approach of surgical intent inferencing. In that paper we focus, however, on team performance by considering three medical professionals: an ophthalmologist, an anesthesiologist, and an OR nurse. In doing so, we computed several gap values from different possible team situations and identified in which situation the team is more prone to risk than others. This experimental study is based on the case published by B. Jericho at the Illinois Medical Center [30]. Although the devastating event was prevented after the surgeon reverified the surgical site in the original case report, we explored hypothetical scenarios in order to address other potential sources of errors based on the case.

Case Study

An 18-year-old male with a history of tobacco, alcohol, and substance abuse came to the hospital with blindness caused by a gunshot wound that he sustained five months ago. His injured left globe caused the blindness. His left eye became blind, painful, and phthisical (involuted). He was scheduled for two consecutive procedures under general anesthesia: left enucleation



[redacted]

FIGURE 9.7 Tattoo with “ILL” in right eye and surgical mark in left eye [4].

with placement of an orbital implant, and left suture tarsorrhaphy. Despite the patient’s ophthalmologic problem, his vital signs were all normal. In addition, he had a dark blue tattoo near his right eye with the initials “ILL”. In order to indicate the correct site for the surgery, the left eye was appropriately marked as shown in Figure 9.7.

A preoperative nurse inspecting the care of the patient initially took the tattoo of initials as the surgical site marking and prepared the right eye for surgery. Although there was a chance to reverify the correct site of the operation as indicated on the consent form, the OR nurse confirmed that the tattoo of initials near the right eye was the surgical site marking and proceeded with the surgery without checking against the surgical consent form. Both the anesthesiologist and the ophthalmologist performed the operation on the right eye of the patient, and the medical mistake was discovered when the patient recovered several hours later. To prevent this devastating event, the surgeon should have clarified the correct site of surgery before the operation by examining the patient’s consent form, medical history, and condition. If any of the medical care members had reverified the correct site of the operation and covered the tattoo with opaque tape to avoid further confusion in the OR prior to the surgery, this adverse event could have been prevented.

Simulation Results

We built BKBs for three medical care members associated with the case: the ophthalmologist, the anesthesiologist, and the OR nurse. The BKBs, were

TABLE 9.1 Size of BKBs

	RVS.	I-no.	CONN.	S-no. (Rules)	Cond.
Ophthal.	32	112	4.02	149	2.02
Anesthesia	13	33	4.88	60	1.68
OR nurse	21	52	4.48	82	1.84

constructed based on the behavioral patterns and the perceptions of the care members in the OR. Table 9.1 shows the overall scale of BKBs, including the number of random variables (RVS.), the number of I-nodes (I-no.), the average connectivity (CONN.), the number of S-nodes (rules) (S-no.), and the average number of conditions for each rule contained (Cond.) in the BKBs. Through belief revision with the BKBs, each care member's intent was inferred by computing the most probable world, composed of random variables under consideration. We assumed that all care team members' intentions and beliefs are identified while they determine the procedures or actions to be taken.

While simulating the case study, we considered the vital signs with body temperature, pulse rate, and respiration rate. When the body temperature is within the range 97.8 to 99°F, the pulse rate is within 60 to 100 beats per minute, and the respiration rate is within 15 to 20 breaths per minute, we assume that the patient is durable for surgery. For surgical procedures, we considered two types of eye surgeries: enucleation (65105) and evisceration (65093). While performing evisceration, the surgeon removes the ocular contents but preserves sclera and sometimes the cornea. While performing enucleation, the surgeon removes the entire globe and a portion of anterior optic nerve. For some patients who are not durable for any type of enucleation, we consider evisceration (65093) as an alternative with less anatomical disruption. To speculate the site of operation associated with medical errors in the experiments, we separate each procedure into two parts: in this case, L65105 and R65105.

Surgeon (Ophthalmologist's) BKB An ophthalmologist diagnoses a patient based on his condition, such as blindness, pain, and phthisis (involuted). When the patient has all the ophthalmological problems in his left eye, the ophthalmologist considers the vital sign of the patient before he decides a potential procedure to be taken. As shown in Table 9.2, the surgeon diagnoses enucleation (65105) for the patient's left side with a high probability, but he may also choose evisceration (65093) without serious consideration of the wound even if it is less likely. It is possible for him to plan enucleation on the right side by mistake with a low probability. We validated the surgeon's diagnosis with the evidence of the right side as well, as shown in Table 9.2.

TABLE 9.2 Surgeon's Diagnosis

Evidence				Target Variables	probability
(B)Blind	(B)Pain	(B)Phthisis	(B)Tattoo	(B)Diagnosis	
left	left	left	right	L65105	2.91655e-08
				L65093	8.74964e-09
				R65105	3.64569e-09
right	right	right	left	R65105	2.91655e-08
				R65093	8.74964e-09
				L65105	3.64569e-09

In addition to the patient's symptoms relevant to the ophthalmological problems, the surgeon considers the vital signs of a patient when determining the procedure to be taken. When all three major vital signs are within the normal range (which are represented by (B)Pulse_rate=normal, (B)Respiration_rate=normal, and (B)Body_temp=normal in the BKB, a surgeon can consider the patient durable for both procedures with the highest probability, which is denoted by "Y" in Table 9.3.

When the patient has a high or low body temperature while his other vital signs are normal, a surgeon can consider the patient durable for evisceration (65093) but not for enucleation (65105). If any other vital sign of a patient is out of the normal range, the surgeon considers the patient not durable for either of the two procedures with the highest probability. We investigated how a patient's durability is inferred from the patient's vital signs and obtained the results we expected, as shown in Table 9.3. We omitted from Table 9.3 cases in which the surgeon determines that the patient is not durable for either procedure under consideration, since they are beyond our research focus.

In addition to the aforementioned patient information, a surgeon determines a procedure based on his personal preference. We implemented a surgeon's

TABLE 9.3 Vital Signs

Evidence			Target Variables	
(B)Pulse	(B)Respiration	(B)Body	(B)Condition_65105	(B)Condition_65093
low	low	low	N	N
normal	normal	low	N	Y
normal	normal	normal	Y	Y
normal	normal	high	N	Y
high	high	high	N	N

TABLE 9.4 Surgeon's Competence Inferencing

Evidence				Target Variables
(X)Experience	(X)Malpractice	(X)Complexity	(X)Fatigue	(X)Competence
low	high	high	high	low
medium	high	high	high	medium
medium	medium	medium	medium	medium
medium	medium	medium	high	low
high	low	low	low	high
high	low	low	medium	medium
high	low	low	high	low
high	low	medium	low	medium

personal preference in choosing a medical procedure with (X)Competence, as shown in Table 9.4. In particular, we included four factors (experience, malpractice, complexity, and fatigue) for implementing the component for inferencing a surgeon's personal competence. We assume an increasing personal competence level as the level of experience increases, or as the level of malpractice, complexity, or fatigue decreases. For example, when a surgeon has a level of low experience, high malpractice, high complexity, and high fatigue, her competence level becomes low. However, if her level of experience increases to the level of medium, her competence level advances to medium when other factors remain the same. Among all possible states, we provide only eight interesting states here to explain how each of these factors influences a surgeon's personal competence. Although a surgeon's personal competence decreases with increasing level of fatigue in general, the competence level remains the same sometimes despite a change in the surgeon's fatigue level. For example, when a surgeon has a level of low experience, high malpractice, and high complexity, her level of personal competence is assumed as low with the highest probability, regardless of her fatigue level, since her best personal competence level is low and can barely be improved or worsened with the change of her fatigue level. Through this design, we made the level of experience more influential than other factors, although it is not a dominant factor.

We assume that a surgeon's competence influences her probability of making a mistake in determining a correct procedure. Therefore, as the level of competence decreases, the error probability increases while the probability of performing correct procedure decreases. As shown in Table 9.5, we validated the ophthalmologist's BKB with a set of evidence including three different levels of personal competence.

TABLE 9.5 Influence of Personal Competence

Evidence					Target Variables	Probability
(B)Blind	(B)Pain	(B)Phthisis	(B)Tattoo	(X)Competence	(B)proc	
left	left	left	right	high	L65105	2.91655e-08
					L65093	2.18741e-09
					R65105	3.64569e-10
left	left	left	right	medium	L65105	2.55198e-08
					L65093	4.37482e-09
					R65105	1.82284e-09
left	left	left	right	low	L65105	1.82284e-08
					L65093	8.74964e-09
					R65105	3.64569e-09

Based on the medical situations involved, a surgeon's next action is determined. Table 9.6 represents a surgeon's next action, as predicted with the corresponding evidence set. With respect to enucleation (65105) procedure, we considered a course of action as follows:

A1. Open and order the OR nurse to hold the eyelids.
A2. Trim away the external coats of the eye from the eyeball.
A3. Trim away the extraocular muscles from the eye surface.
A4. Cut the optic nerve.
A5. Remove the entire eyeball.
A6. Put an orbital implant into the socket.
A7. Close the tissues and do tarsorrhaphy.

TABLE 9.6 Next Action Prediction

Evidence								Target Variables
(B)A1	(B)A2	(B)A3	(B)A4	(B)A5	(B)A6	(B)A7	(B)Nurse	(A)Action
N	N	N	N	N	N	N	Na	A1
Y	N	N	N	N	N	N	N	Waiting
Y	N	N	N	N	N	N	Y	A2
Y	Y	N	N	N	N	N	Na	A3
Y	Y	Y	N	N	N	N	Na	A4
Y	Y	Y	Y	N	N	N	Na	A5
Y	Y	Y	Y	Y	N	N	Na	A6
Y	Y	Y	Y	Y	N	N	Na	A7

When none of the actions are completed, a surgeon is supposed to take action A1. After the surgeon completes action A1 [represented as $(B)A1 =$ Y in Table 9.6], the surgeon's next action depends on his belief about the nurse's status. If the nurse is ready to hold the patient's eyelid, the surgeon performs the next action (A2). Otherwise, the surgeon waits for the nurse to be ready to assist. For her subsequent actions, the surgeon does not rely on her belief on the nurse, but rather, determines her next action depending on the completeness of her prior actions.

Anesthesiologist's BKB The duty of the anesthesiologist consists mainly of selecting anesthesia prior to the surgery and adjusting anesthesia if necessary during the surgery. Prior to a surgery, the anesthesiologist interviews the patient to form a detailed plan about anesthesia injection and to learn about precautions that must be addressed. During the surgery, the anesthesiologist monitors the patient's vital signs and acts according to the patient's physical state. Similar to the surgeon's BKB, the anesthesiologist's personal competence is inferred from his level of experience and fatigue, as shown in Table 9.7.

With regard to medical errors, we assume that a highly competent anesthesiologist can better select and administer anesthesia than an anesthesiologist of low competentcy. To validate the hypothesis, we varied the personal competence of the anesthesiologist and observed how the chance of making a mistake in determining anesthesia was changed. As we expected, the results obtained show that the probability that the anesthesiologist will select and administer an appropriate anesthesia increases, while the probability of his making mistakes decreases with increasing personal competence, as shown in Table 9.8.

In addition to the personal competence and its impact on the probability of medical errors, we addressed an anesthesiologist's decision making in selecting an appropriate anesthesia for the patient. In our current model, we considered diabetes and cardiovascular and pulmonary problems, since these

TABLE 9.7 Inference of Personal Competence

Evidence		Target Variables
(X)Experience	(X)Fatigue	(X)Competence
low	high	low
low	low	medium
high	low	high
high	high	medium

TABLE 9.8 Influence of Personal Competence

Evidence					Target Variables	Probability
(B)Blind	(B)Pain	(B)Phthisis	(B)Tattoo	(X)Com	(G)Anesthesia	
left	left	left	right	high	General	1.64025e-06
					Left_local	3.2805e-07
left	left	left	right	medium	General	1.47622e-06
					Left_local	4.92075e-07
left	left	left	right	low	General	1.3122e-06
					Left_local	6.561e-07

are critical conditions leading to fatal consequences under general anesthesia. When the patient has any of these critical diseases, the anesthesiologist needs to use local anesthesia, even if general anesthesia is preferred for eye surgeries such as enucleation or evisceration. We varied the patient's condition and confirmed that the results obtained are consistent with expectation, as shown in Table 9.8. The target variable, (B)General_refused=Y, denotes the patient's condition, which is too risky for general anesthesia.

We assumed the course of actions for the anesthesiologist as "choose_drug→injection→infiltration→monitoring." To implement this, we introduced four random variables: (B)Choose_drug, (B)Injection, (B)Infiltration, and (B)Monitoring, and represent different status levels of the OR by instantiating these random variables differently. As shown in Table 9.10, the anesthesiologist's BKB correctly predicted the next action to take, as we expected.

OR Nurse's BKB To validate that the nurse's model is a true representation of a real nurse's decision making, we focused on how the nurse's personal competence is inferred from his experience and fatigue and how the nurse determines the correct action to take in any given situation. First, the inference

Au: Please provide citation of Table 9.9.

TABLE 9.9 Validation for Selecting Anesthesia

Evidence			Target Variables
(B)Diabetes	(B)Cardiovascular	(B)Pulmonary	(B)General_refused
N	N	N	N
Y	N	N	Y
N	Y	N	Y
N	N	Y	Y

TABLE 9.10 Validation of Actions

Evidence				Target Variable
(B)Choose_drug	(B)Injection	(B)Infiltration	(B)Monitoring	(A)Action
N	N	N	N	Choose_drug
Y	N	N	N	Injection
Y	Y	N	N	Infiltration
Y	Y	Y	N	Monitoring

of the nurse's personal competence was tested. We assumed that the nurse's personal competence increases as the nurse's level of experience increases or the level of fatigue decreases. The states of target variables in Table 9.11 show the results obtained, which are consistent with our assumption.

We also assume that the chance of making a mistake depends on the nurse's personal competence. The OR nurse can make two types of mistakes: He can misunderstand the surgeon's order, or he can misunderstand the patient's condition. Occasionally, OR nurses assume a different procedure to be determined by the surgeon, due to his lack of knowledge or experience. Since the nurse's actions depend heavily on the procedure to be performed by the surgeon, his misunderstanding of the surgeon's intent can lead to an adverse outcome. With increasing personal competence, the chance that the nurse understands other team members correctly increases, while the chance that the nurse makes mistakes decreases. Table 9.12 validates how the probability changes with the varying personal competence level of the OR nurse.

We assumed that the nurse performs three types of actions: checking the patient's vital signs, waiting for the order, and following the order, which is "hold_eyelid" in this case. As shown in Table 9.13, the nurse waits for the surgeon to give an order when there is no urgency (i.e., the patient's vital signs are within the normal range) or for a specific order to take. When the surgeon orders a certain action, the OR nurse follows the order. When the patient's vital signs move dramatically [i.e., (B)Vital_request=Y], the OR

TABLE 9.11 Inference of Personal Competence

Evidence		Target Variables
(X)Experience	(X)Fatigue	(X)Competence
low	high	low
low	low	medium
high	low	high
high	high	medium

TABLE 9.12 Influence of Personal Competence

Evidence					Target Variables	Probability
(B)Blind	(B)Pain	(B)Phthisis	(B)Tattoo	(X)Competence	(G)Nast	
left	left	left	right	high	L65105	1.77147e-06
					R65105	3.54294e-07
					L65093	5.31441e-07
				medium	L65105	1.41718e-06
					R65105	4.25153e-07
					L65093	5.6687e-07
				low	L65105	1.06288e-06
					R65105	4.60582e-07
					L65093	6.023e-07

nurse checks the cause of the fluctuation and follows the emergency care routine. Although we assigned a higher priority to emergency care than to the surgeon's order ("hold_eyelid"), these can be hardly separated in practice. We list the experiment setting and results in Table 9.13.

Gap Analysis We assume that medical errors occur when there is a significant discrepancy among the team members' intent. By comparing individuals' intents, we aim to determine whether or not a team has a high risk. Due to the complexity of the OR and medical processes, the number of possible worlds associated with the case can be tremendous. Even if we consider incomplete and inaccurate worlds of information in our research, the number of possible worlds under consideration is still intractable. To show the applicability of our gap analysis in identifying situations having a high risk of medical errors, in this section we consider a few situations as examples.

S1: No risk of medical error. A patient has an ophthalmological problem in his left eye, and all care members agree on performing enucleation (65105)

TABLE 9.13 Validation with the Planned Procedure of Nurse

Evidence		Target Variable
(B)Order_to_hold	(B)Vital_request	(A)action
N	N	Waiting
Y	N	Hold_eyelid
N	Y	Check_vital
Y	Y	Check_vital

on the left eye of the patient. With respect to medical errors, this situation is normal and we assume there to be no gap in the team composed of those medical professionals.

S2: Wrong-side preparation. A patient has an ophthalmological problem in his left eye, but the OR nurse makes a mistake while preparing the surgery because of the confusing tattoo near the right eye.

S3: Wrong-side operation. A patient has an ophthalmological problem in his left eye, but the ophthalmologist was disoriented by body symmetry when he read the patient's CT before the operation. He determined to perform enucleation (65105) on the right side.

S4: Misdiagnosis. The ophthalmologist decides to perform evisceration (65093) for the patient without recognizing a severe phithisis on the left eye and expects other care members to work for the same procedure. However, the anesthesiologist and the OR nurse know the patient's condition correctly and expect the ophthalmologist to perform enucleation (65105).

S5: Wrong anesthesia. A patient has an ophthalmological problem in his left eye and the ophthalmologist and the OR nurse prepare the enucleation (65105) on the patient's left side. However, the anesthesiologist decides to use local anesthesia since he was confused by another patient who had diabetes. Even if the patient has a severe phthisis, the anesthesiologist expects other care members to perform evisceration (65093).

As shown in Table 9.14, several medical errors are possible for various reasons, even if the same evidence is given. From the ophthalmologist's perspective, (G)Plan indicates the medical procedure to be taken. From the anesthesiologist's perspective, (G)Plan is to select and administer an appropriate anesthesia. From the OR nurse's perspective, (G)Plan is the procedure in which he assists. In each team member's intent inferencing, his or her belief of other team members was also inferred with the given evidence. For example, the ophthalmologist believes that the anesthesiologist would determine general anesthesia and the OR nurse would assist enucleation on the left side when the ophthalmologist decided to perform enucleation on the left side of

TABLE 9.14 Comparison of Hypothetical Situations

	Description	Ophthalmologist (G)Plan	Anesthesiologist (G)Plan	OR Nurse (G)Plan
S1	Correct	L65105	general	L65105
S2	Wrong-side preparation	L65105	general	R65105
S3	Wrong-side operation	R65105	general	L65105
S4	Misdiagnosis	L65093	general	L65105
S5	Wrong anesthesia	L65105	Left_local	L65105

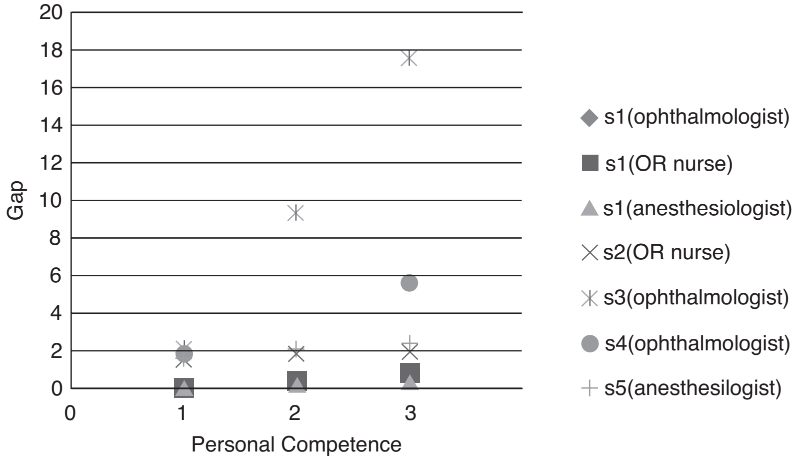


FIGURE 9.8 Team members' personal competences vs. gap.

the patient (i.e., L65105). The shaded cells denote that the medical professionals have different intents and beliefs than other care members, causing a discrepancy in the team intent. To validate the applicability of gap analysis, we varied each member's personal competence and computed the gap value according to equation (9.1). We assume that losing personal competence increases the gap among the team members and leads to a situation riskier than others. As shown in Figure 9.8, we investigated all five situations with varying team members' personal competence level. Three different levels were considered for each medical professional. On the *x*-axis, 1 denotes the highest and 3 the lowest competence level. The *y*-axis represents the gap value computed by equation (9.1). For all team members, the gap values computed increase as the personal competence level is degraded. Considering the situation with respect to a team member's role, we varied the ophthalmologist's competence level for situations S1, S3, and S4, the anesthesiologist's competence level for situations S1 and S5, and the OR nurse's competence for situations S1 and S2.

While computing the gap values with the probabilities obtained from belief revision, we considered the highly competent team member as a baseline in each situation. Through the experiments conducted with varying personal competence of all team members, we confirmed that the BKBs' representing capability was consistent with our expectation.

CONCLUSION

In this study we present a **cognitive computational framework** to simulate the reasoning processes of medical team members to reduce medical errors by identifying and resolving gaps among individual care members. Communication breakdown among medical team members has been known to be a major cause of adverse events, and we expect our approach to contribute to diminishing the communication loss and assisting medical care members to better understand the dynamic environments and their co-workers. Among various types of medical errors, thus far we have investigated miscommunication among medical team members caused by misdiagnosis, wrong-site operation, and wrong anesthesia. To accomplish our ultimate research goal, promoting patient safety in the OR, it is necessary to simulate other types of errors, by investigating more test cases.

We consider two future directions: temporal relationships among pieces of information and generalization among various medical procedures. To simulate medical cases dynamically, reasoning and inferencing knowledge with respect to time is essential. Although there is a theory regarding temporal BKBs, the computational complexity hinders its applicability [46]. In addition, general components of surgical intent inferencing need to be formulated, which would be different from the hierarchy of intent inferencing in other domains.

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KEY TERMS

intent inferencing
team intent
gap
Bayesian knowledge bases
checklisting
reasoning processes
cognitive computational framework

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