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Digital Cognitive Aids to Support Adaptation of Surgical Processes to COVID-19 Protective Policies

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***Abstract*—Surgical processes are rapidly being adapted to address the COVID-19 pandemic, with changes in procedures and responsibilities being made to protect both patients and medical teams. These process changes put new cognitive demands on the medical team and increase the likelihood of miscommunication, lapses in judgment, and medical errors. We describe two process model driven cognitive aids, referred to as the Narrative View and the Smart Checklist View, generated automatically from models of the processes. The immediate perceived utility of these cognitive aids is to support medical simulations, particularly when frequent adaptations are needed to quickly respond to changing operating room guidelines.**

Keywords—situational awareness, process modeling, cognitive aid, COVID-19

I. Introduction

New evidence from the Chinese Center for Disease Control and Prevention suggests that 5-10% of COVID-19 patients require intensive care unit admission and mechanical ventilation [1]. Critically, mechanical ventilation is one of several procedures categorized as 'aerosol-generating', including intubation, suctioning, and extubation. Aerosol-generating procedures are important to consider in the context of COVID-19 due to the high risk they pose to providers; these procedures necessitate close contact with aerosolized viral particles [2], increasing the likelihood of infection. Thus, aerosol-generating surgical procedures have changed and will continue to evolve to incorporate new COVID-19 adaptations to improve the safety of at-risk patients and their medical teams.

Surgical procedures are often inherently complex involving aspects such as multiple specialty teams, hierarchical task decomposition, concurrent tasks, team communication, resource management, and non-normative (i.e., exceptional or unusual) situations. Aerosol-generating surgical procedures become even more complex when adaptations must be made for suspected COVID-19 positive cases, introducing additional medical personnel, different resource management considerations, and modifications to the existing tasks. This complexity requires additional cognitive resources and increases the likelihood of miscommunication, lapses in judgment, and medical error, which can have serious health impacts for both the patient and the medical team. In this context, it is crucial that the medical teams' process familiarity is up-to-date for such procedures. Existing evidence supports the utility of cognitive aids in healthcare as a means to maintain optimal performance [e.g., 3]. Additionally, research has shown that using human simulations to train medical teams also improves their performance [e.g., 4].

We propose an approach to automatically generate two kinds of cognitive aids for the medical team based on detailed, rigorously defined, validated surgical process models that capture best practices and incorporate COVID-19 adaptations. The first kind of process-model-driven cognitive aid, the Narrative View, is a hypertext document allowing the medical team members to explore all possible scenarios within the procedure. The second kind of process-model-driven cognitive aid, the Smart Checklist View, is a situationally-aware electronic checklist dynamically updated to show an on-going scenario, including the past, current, and possible future tasks (or steps).

Both of these cognitive aids have immediate utility as interactive simulation instruments, with the longer-term potential to provide real-time guidance to the medical team in a clinical setting. These cognitive aids are automatically generated from a process model, such that when the models are updated to reflect new adaptations in the process, the aids can be easily

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regenerated to reflect those adaptations. Our primary objective is to show how this kind of approach can aid in introducing new process changes in a systematic way and can provide cognitive support as complex medical processes change frequently to support new medical guidelines and treatment plans (e.g., surgical procedures adapted for COVID pandemics, in-patient chemotherapy adapted for new treatment plans).

II. Approach

Whether the patient is symptomatic for COVID-19 or not, the process model and the surgical team should anticipate a positive test result. Therefore, for this work, the surgical process model needs to capture the recommended standard surgical procedure and the most up-to-date COVID-19 adaptations for that procedure. In our approach, that model defines the surgical process as a hierarchical decomposition of steps capturing the normative scenarios as well as non-normative scenarios where a problem is identified and then must be addressed. The detailed, precisely defined, validated surgical process models are used to automatically generate both cognitive aids. These aids show context-aware process information about the specialty teams and their steps. Each specialty team should have a clear picture of their process steps in the current context as well as understand their interactions with other teams in that context.

The models of the surgical processes need to be expressive enough to capture the inherent complexity of these processes. For this work, the models also need to have rigorous execution semantics to support both automated analyses and automated generation of the cognitive aids. We use the Little-JIL process modeling language [5] that satisfies both of these needs. The process validation techniques [6] include manual reviews as well as automated analyses (e.g., model checking and fault tree analysis). Such techniques help ensure that these models accurately reflect the real-world processes and detect defects in the models (or in the actual procedures) that could cause harm to the patient or medical team.

The surgical process model with any COVID-19 adaptation is used to automatically generate the two different process-model-driven cognitive aids. The Narration Generator tool automatically generates the Narrative View providing a static, context-aware hypertext document describing all of the potential scenarios captured in that process model. The Smart Checklist toolset [7] provides dynamic, context-aware process information about the patient, medical team, and the steps recently completed, the steps currently being done, and optionally the potential impending next steps. This Smart Checklist View is updated based on real-time monitoring of process execution events received from human process performers and from the *Open Integrated Clinical Environment (OpenICE)* [8]. OpenICE is an open-source platform for integrating data from multiple medical devices and hosting applications that use device data and may issue commands to devices.

During this current pandemic, the surgical process models have frequently needed to be changed to incorporate the most recent COVID-19 adaptations, and it is likely that such changes will continue to occur. Thus, it is important to re-validate the modified process models to gain assurance that the updates do not introduce defects that could harm the patients or the medical teams. The re-validated process models can then be used to automatically regenerate the cognitive aids to bring them up-to-date.

III. Eliciting, Rigorously Defining, and Validating Surgical Process Models with COVID-19 Adaptations

Cardiac surgeries are a critical target of concern since they rely on many aerosol-generating procedures, including trans-esophageal echocardiography and intubation, and recent analyses have shown that patients with pre-existing cardio-vascular disease typically experience worse outcomes when exposed to COVID-19 [9].

In previous work, we developed Little-JIL process models of two common cardiac surgeries, aortic valve replacement and coronary artery bypass grafting [10]. Recently, the COVID-19 OR guidelines [11] were published to describe the recommended adaptations for suspected COVID-19 positive patients undergoing such aerosol-generating surgical procedures. For this work, the two surgical process models are being updated based on these guidelines, as well as local hospital documentation and domain expert interviews.

A. Eliciting surgical process models with COVID-19 adaptations

These two cardiac surgery procedures typically involve a medical team consisting of at least the following specialty teams: Anesthesia (Anesthesiologist), OR Nursing (Circulating Nurse and Scrub Nurse), Surgery (Surgeon), and a Perfusionist to operate the heart-lung machine. The primary team consists of these four specialty teams. To support the COVID-19 adaptations, there is a secondary team consisting of a Nurse in Charge, two OR Runners, an OR Technician for the OR Nursing team, and an Anesthesia Nurse for the Anesthesia team.

One goal of the COVID-19 adaptations is to minimize the number of team members as well as the amount of equipment and consumables in the operating room (OR) to try to decrease physical interactions that could lead to viral exposure. Another goal of these adaptations is to reduce the amount of PPE (Personal Protective Equipment) and other consumables used and to limit the amount of equipment needing cleaning. The COVID-19 adaptations consist of the following phases: Preparation, Intra-Operative, Post- Operative, and Follow Up. (These adaptations are for all surgical procedures and cover the Anesthesia, OR Nursing, and Surgery teams. The adaptations are being extended for cardiac surgery to include the Perfusion team.)

To comply with the COVID-19 adaptations, all team members except for the Nurse in Charge don full PPE and/or PAPR (Powered Air Purifying Respirators). For all phases, the Nurse in Charge and OR Runners generally remain outside the OR while the Anesthesia team and OR Nursing team typically remain in the OR. The Surgery team usually enters the OR after the intubation of the patient. In the Preparation and Post-Operative phases, the patient is carefully transferred within the hospital to reduce their contact with other people.

B. *Rigorously defining these process models*

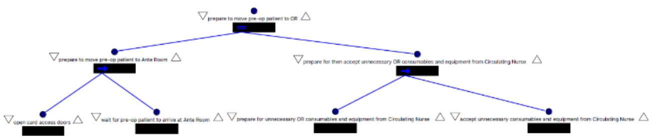

Fig. 1. Part of the Little-JIL process model for subprocess **Perform OR Runner Tasks**, specifically step **prepare to move pre-op patient to OR**

We are actively developing a Little-JIL process model for the **Preparation** phase. This process model consists of the following high-level steps carried out concurrently: **perform Nurse in Charge tasks, perform OR Runner tasks, perform OR Nursing team tasks, perform Anesthesia team tasks**.

Fig. 1 shows part of the subprocess model for **perform OR Runner tasks**, specifically the step **prepare to move pre-op patient to OR**. Little-JIL steps are depicted as step bars, black rectangles whose names appear as text above them. Solid blue lines below a step bar point to sub-steps that comprise the step's decomposition. The possible Little- JIL sub-step orderings (depicted by the icons shown on the left-hand side of the step bars) are: sequential, parallel (i.e., concurrent), try, and choice. In this Figure, the step **prepare to move pre-op patient to OR** performs the following two concurrent steps (indicated by the equal sign in the step bar): **prepare to move pre-op patient to Ante Room and prepare for then accept unnecessary OR consumables and equipment for Circulating Nurse**.

The first step **prepare to move pre-op patient to Ante Room** sequentially executes the following steps: **open card access doors** and **wait for pre-op patient to arrive at Ante Room**. In the subprocess **Perform OR Nursing tasks**, the OR Nursing team categorizes the OR consumables and equipment into necessary and unnecessary. The necessary consumables and equipment remain in the OR. The necessary equipment is covered in clean plastic if it can be feasibly used that way. In the subprocess **Perform OR Runner tasks**, the second step **prepare for then accept unnecessary OR consumables and equipment from Circulating Nurse** first performs step **prepare for unnecessary OR consumables and equipment** and then step **accept unnecessary consumables and equipment from Circulating Nurse**. The unnecessary consumables can be conserved in this manner while the unnecessary equipment does not need to be cleaned.This is also an example of a synchronization point between the Circulating Nurse and the OR Runners. Such a synchronization point often requires one team to wait for another team.

C. *Validating the process models*

The process validation techniques we use include manual reviews as well as automated analyses, in particular model checking and fault tree analysis [7]. The cardiac surgery models were manually reviewed by all 4 specialty teams. The COVID-19 adaptations so far have been reviewed by a Nurse in Charge and a Surgeon. These reviews help ensure that these models accurately reflect the real- world processes.

To complement the manual reviews, model checking can determine if there is a scenario through the process model whose execution could cause a violation of a specified requirement, such as one stating that the OR Circulating Nurse must pass the unnecessary consumable and equipment to the OR Runners in the Ante Room before the OR Runners move the patient to the OR. The Little-JIL model checking toolset takes as input a Little-JIL process model along with a requirement (such as the one stated above). This toolset can automatically translate to the input formalisms of two different model checkers. The toolset can then apply these model checkers to their input formalisms to determine if there is a scenario through the process model that could cause a violation of that requirement. Typically, we develop a number of requirements for each process and reapply the model checking whenever the process model is modified.

Fault tree analysis provides descriptions of how unwanted situations (such as the pump and the ventilator both being off) could arise from the incorrect performance of some combination of steps in the process. The Little-JIL fault tree analysis toolset takes as input a Little-JIL process model along with a user-specified hazard, such as the pump and the ventilator example given above. This toolset then automatically generates the fault tree and minimal cut sets capturing the ways the hazard could be caused by different scenarios through the process model involving the incorrect performance of some of the steps. Typically the hazards can be easily updated and revalidated whenever the model is modified.

These validation toolsets, described in more detail elsewhere [e.g., 6], help detect defects in the models (or in the actual procedures) that could lead to harming the patients or the medical team.

IV. AUTOMATICALLY GENERATED PROCESS-MODEL-DRIVEN COGNITIVE AIDS

Even the most well-trained clinicians were not trained to operate under these unique COVID-19-specific conditions. New protocols, which are being actively developed and are constantly evolving, in addition to inexperienced staff, provide additional layers of unfamiliarity. Moreover, appropriate PPE and/or PAPR, required to minimize exposure to aerosolized particles, can contribute to a reduction in communication, situational awareness, and visual fields [2]. To address these challenges, the Narration View and the Smart Checklist View aim to improve the team members' context-awareness while they carry out the latest COVID-19 adaptations. This increased awareness should help ensure the safety of the patient and the medical team.

Our process-model-driven cognitive aids build on work in the areas of digital process guides [e.g., 12] and checklists [e.g., 13]. The digital process guides are automatically generated from a process model and then typically used before performing the real-world processes. The digital checklists are intended for use during process execution, but, with only rare exceptions (e.g., [4]) the processes they represent are hard-coded in their implementations, making it difficult to adapt them to changes in the processes. Moreover, the digital process guides and checklists, unlike our Little-JIL-based approach,typically do not provide support for such complex process features as concurrency, resource management, and exceptional situations inherent in the cardiac surgical procedures. For this work, where the complex medical processes are rapidly changing, the Narrative View and Smart Checklist View are both automatically re-generated from the latest version of the detailed, precisely defined, and validated process models.

D. Narration View

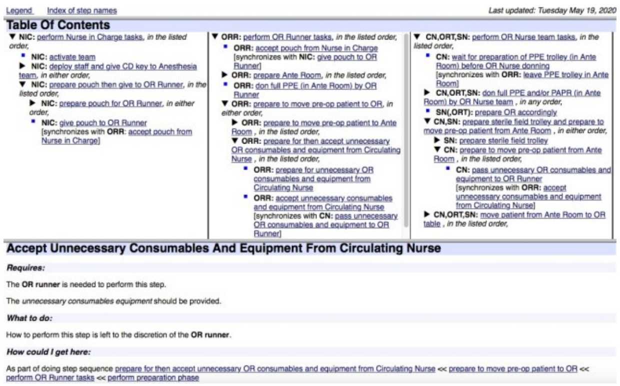

Fig. 2. Part of the Narration View for the COVID-19 Preparation Phase

In the surgical processes with COVID-19 adaptations, multiple specialty teams often concurrently perform their steps. Fig. 2 shows the Narration View for part of the COVID-19 Preparation Phase. In this View, the Table of Contents section displays a Single-Team View for each team showing a listing of that team's step hierarchy. This displays each individual step within its static process context. Below the Table of Contents, the Body section displays additional low-level details about each step. This View also documents when the Little-JIL surgical process model was last updated (shown in the top right corner).

In this Figure, the Single-Team Views from left to right are: Nurse in Charge (NIC), OR Runners (ORR), OR Nursing, consisting of the Circulating Nurse (CN), the Scrub Nurse (SN), and OR Technician (ORT). (The Single-Team View for Anesthesia, not shown here, would be on the far right.) In the step hierarchy, a user would click on the right facing triangle in front of a given step to expand that step's sub-steps or else on the downward facing triangle in front of the step to collapse its sub-steps. For a given team, some of their steps are performed independently from the other teams. In the Single-Team View for the OR Runners (shown in the middle column), **step prepare for unnecessary OR consumables and equipment from Circulating Nurse** (shown towards the bottom of that column) are all performed independently from the other teams. The remaining steps are performed collaboratively with other teams.

Such collaborations often involve a given team synchronizing with the other teams to hand off information or physical objects. These synchronization points can lead one or more of these teams needing to first go on standby, waiting for some of the steps to be completed by the remaining teams, and then continuing to make progress on their own steps. For instance, the OR Runners need to perform step **accept unnecessary consumables and equipment from Circulating Nurse** (shown towards the bottom of the middle column). That step needs to be synchronized with the Circulating Nurse performing step **pass unnecessary OR consumables and equipment to OR Runner**. The user could click on the link to the synchronized step in the given team's step hierarchy to better understand that team's step hierarchy. For the previous example, the link would jump to the bottom of the OR Nursing team's step hierarchy (shown in the right column).

At any time, a user may click on a link to a given step in the Table of Contents to display the low-level details about that step in the Body section. For instance, the Body is displaying the details for step **accept unnecessary consumables and equipment from Circulating Nurse**. These details for the step include the personnel, equipment, and consumables needed to carry out that step (denoted *Requires*) as well as any sub- steps to be carried out for the step (denoted *What to do*). The details also include any information or physical objects produced by normative steps or else any problems identified by non-normative steps (denoted by *Outcomes*). They lastly include different contexts in which the step is used (denoted *How could I get here*).

E. Smart Checklist View

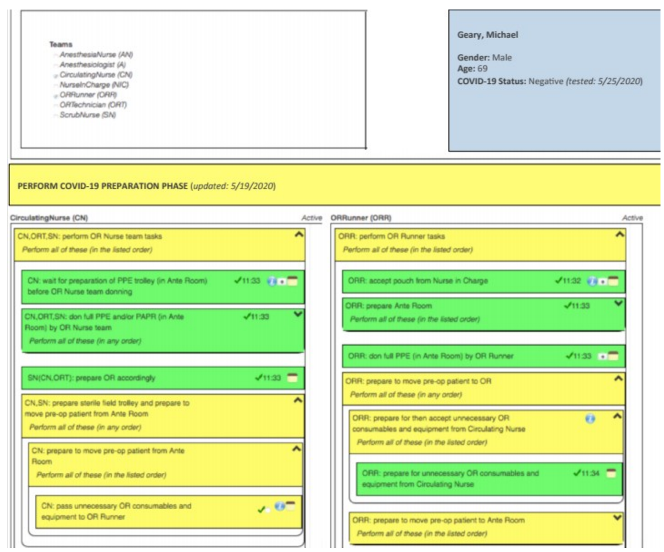

Fig. 3. Part of the Smart Checklist View for the COVID-19 Preparation Phase

Fig. 3 shows the Smart Checklist View for part of the COVID-19 Preparation Phase where the Circulating Nurse and OR Runner are being guided through the COVID-19 adaptations for preparing the OR and then moving the pre-operative patient to the OR. This View provides dynamic, context-aware information about the teams included in the process model (shown on the top left), the patient (shown on the top right), and the step listing (shown on the bottom). The team information lists each team member (and their abbreviated name): Anesthesiologist (A), Anesthesia Nurse (AN), Circulating Nurse (CN), Nurse in Charge (NIC), OR Runner (ORR), OR Technician (ORT), Scrub Nurse (SN). The patient information includes data such as patient identifiers (e.g.,, full name), patient demographics (e.g.,, age), and patient vital signs (e.g.,, heart rate). This section also communicates the patient's COVID-19 status and date of last test. The step listing has two main components: a process header (shown at the top) and a Multi-Team View (shown on the bottom) where there is a Single-Team View for each selected team member displaying their dynamic step listing.

In Fig. 3, the process header displays the name of the process being carried out by the entire team, in this case **PERFORM COVID-19 PREPARATION PHASE** (shown in all capitals on the far left) and the execution status of that process (indicated by the background color), in this case "In progress" (designated by the yellow). This header also displays when the process was last updated (shown in italics next to the process name). In the team member listing, the Circulating Nurse and OR Runner were selected (by clicking on their checkboxes). Thus, the Multi-Team View displays a Single-Team View for the Circulating Nurse (on the left) and for the OR Runner (on the right). In a Single-Team View for a given team, the dynamic step listing displays their completed steps (shown in green) and their currently active steps (shown in yellow). Potential next steps could also be shown if desired (with a white background). The Single-Team Views show the step hierarchy using indentation. User preferences may be used to hide or show the step hierarchy, as well as a number of other features.

In the Circulating Nurse's Single-Team View, the immediate past step is **prepare OR accordingly** (shown by the green background along with the green checkmark icon and the timestamp of "13:00"). The current step is **pass unnecessary OR consumables and equipment to OR Runner** (shown by the yellow background along with the green checkmark radio button). Additionally, this step has an information icon (*i*) which may be clicked to bring up a dialog with a basic help message for the step as well as a note icon which may be clicked to bring up a dialog to type in clinical notes. In this case, the Circulating Nurse, or a designated scribe, clicks on the green checkmark radio button to indicate that the unnecessary consumables and equipment are ready to be passed to the OR Runner.

Fig. 4 shows the updates to the Smart Checklist View after the Circulating Nurse completes step **pass unnecessary OR consumables and equipment to OR Runner**. In the Circulating Nurse Single-Team View, this step is part of the step **prepare to move pre-op patient from Ante Room** (shown with a green background and a green checkmark icon annotated with "13:04"). In the OR Runner Single-Team View, a new current step **accept unnecessary consumables and equipment from Circulating Nurse** (shown with a yellow background and a green checkmark radio button) is added at the bottom. This step is an example of a synchronization point between the Circulating Nurse and the OR Runner where one of them may need to go on standby. For the on-going training simulation, the team members would continue to complete their current steps until they complete the entire process.

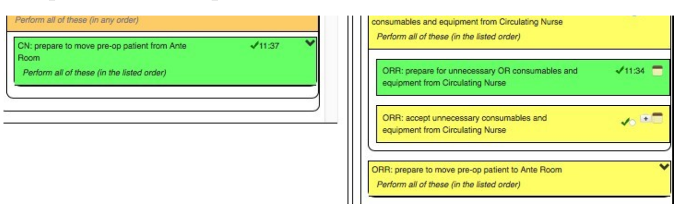

Fig. 4. Updated Smart Checklist View after the Circulating Nurse successfully completes the step "pass the unnecessary consumables and equipment to the OR Runner"

V. Discussion

Given the recent changes imposed by the COVID-19 pandemic, OR teams currently need to rapidly change how they carry out aerosol-generating procedures to adapt for possible COVID- 19-specific complications. Adapting to these new demands increases the surgical team's cognitive load, thereby increasing the potential of errors that could harm the patients, their medical team, or both.

The Narrative View, generated by our approach, can be used by medical providers to manually review changes to processes before deploying these changes in the real-world processes. This View also presents the opportunity to rehearse or practice several possible scenarios prior to initial exposure, either through team-based medical simulation or individual mental practice approaches. Mental practice, defined as "the cognitive rehearsal of a task before performance," has proven to be an effective method of enhancing technical skills in surgery, demonstrated notably through a randomized controlled study [12]. In addition to improving technical skills, mental practice was further shown to be an effective stress management tool, indicated by a reduction in subjective, cardiovascular, and neuroendocrine responses [13]. By consulting the process-model-driven checklists developed according to current medical best practice and leveraging cognitive engineering approaches [14], users are expected to regain cognitive resources to devote to surgical care. Errors based on faulty memory recall should be diminished, given the guidance provided by the checklist, while team situation awareness is expected to concurrently improve.

Relying on a digital platform to deliver a checklist is accompanied by a number of benefits as well. One such benefit we are starting to investigate is the opportunity for hands-free guidance. Incorporating speech recognition to initiate the checklist, and speech generation to guide the user through the process, should reduce tactile interaction and perhaps the number of individuals required. In one study, although 85% of checklist items were checked off as complete, review of the medical record revealed that only 54% of these tasks were actually completed [15]. Given the digital format of the Smart Checklist, we will have the ability to cross-reference timestamped checklist interactions with ground truth via activity logs and medical device logs including the OpenICE data log to determine the nature of checklist compliance, extending previous work from trauma resuscitation settings [16] into the cardiac OR.

Our near-term goal is to evaluate the proposed approach by applying it to cardiac surgery process models, initially created for previous work and now modified to adapt to the changing conditions and information connected to the COVID-19 pandemic. This kind of approach also can be more broadly applied to provide cognitive support for adapting to process changes needed to implement the most up-to-date best practices in other complex medical procedures (e.g., chemotherapy treatment plans).

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