Provably Clean: A Formal Analysis of Hand Hygiene During Anesthesiology Induction

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Provably Clean: A Formal Analysis of Hand Hygiene During Anesthesiology Induction

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***Abstract*—Healthcare-acquired infections (HAIs) are a serious problem in operating rooms. Anesthesia providers' hand hygiene during induction is often cited as a major contributor to this problem. HAIs can lead to grave consequences such as sepsis and death. Proper infection control practices are expected to be in place. However, multiple people working concurrently results in more hands with less clearly defined roles. This makes the process more complex and error-prone. Moreover, anesthesia induction is a rapid procedure that may make it difficult for practitioners to remember to clean their hands. Previous work sought to address this problem using a novel computational method based on model checking. This allowed an analyst to model an induction process and prove whether the procedure would ever allow things that should remain clean to become dirty. In this work, we extended this method's capabilities and used it to evaluate the induction procedure used at a large, mid-Atlantic, academic medical center. To accomplish this, we conducted observations and used this information to construct a model of a real anesthesiology induction procedure. We then used the method to evaluate this normative procedure, but we also introduced modifications that included nondeterministic factors such as skipping steps and accidentally touching hands together. Finally, we accounted for the possibility of improperly cleaning equipment between patients. By analyzing these models, we discovered that the evaluated induction procedure was robust both normatively and to practitioners skipping hand hygiene steps. However, we found two ways improperly cleaned equipment could allow serious patient cross-contamination. We discuss the importance of these findings and make recommendations for improving anesthesiology induction protocols and the analysis method we used.**

***Index Terms*—process improvement; healthcare systems; formal methods; human behavior modeling**

I. Introduction

Healthcare-associated infections (HAI) are a serious problem in operating rooms (ORs) ,where they impact 7% of surgery patients [1]. HAIs can have grave consequences such as sepsis and death, and complications caused by OR HAIs cost the healthcare industry more than $45 billion annually [1]. Multiple studies have identified anesthesia provider hand hygiene as a potential source for HAIs in the OR (see [2] for a review). Thus, understanding how anesthesia providers' hand hygiene behavior can interact with OR procedures to spread and/or prevent the spread of infectious agents is essential to patient safety. Patients are particularly vulnerable during anesthesia induction procedures due to the intimate contact anesthesia providers have with the patient's blood and respiratory systems. In this procedure, if sanitization practices are not adhered to, bacteria may enter a patient's body. Additionally, infectious agents can spread around the OR, increasing the risk of patient cross-infection. Proper infection control practices are expected to prevent these consequences and keep the patients safe. However, multiple people working concurrently result in more hands with unclear roles, making the process more complex and error-prone. Moreover, anesthesia induction is a rapid procedure that can make it difficult for practitioners to remember to sanitize their hands properly or remove gloves between steps.

This paper describes how we used formal methods (tools and techniques designed to prove the properties of complex systems) to determine how HAIs can spread through the anesthesia induction process. To do this, we modeled the induction process used by a large medical center. We then used model-checking analyses (automated mathematical proofs) to evaluate the overall safety of the normative procedure. We also used these analyses to explore expected ways that standard practices could be violated to determine which hygiene practices are most critical to infection prevention.

In what follows, we provide the background necessary for understanding our methods, a clear statement of our overall research objectives, and a detailed description of our methods. We then present our results and discuss their implications for anesthesiology. We also explore directions for future work.

II. Background

Below, we present background information on topics important for understanding the presented research. This includes descriptions of the anesthesiology induction process and the formal methods concepts we employed. Terms specific to both domains are described in the glossary at the end of the paper.

A. The Anesthesiology Induction Process

Anesthesia induction is a critical phase in which patients are prepared for surgery by being rendered unconscious. The procedure starts with checking the patient's vital signs and preoxygenation. This is accomplished by placing an oxygen mask on the patient and having the patient breathe

100% oxygen for one to two minutes. Once the patient is preoxygenated, the anesthesia provider administers sedatives and neuromuscular paralytics agents. These are administered by connecting syringes to a port and injecting and flushing the port. Once the patient is unconscious, the provider inserts an oropharyngeal airway and then performs bag/mask ventilate. After about two minutes of such ventilation, the oxygen mask is removed from the patient and placed on a holder. The provider then uses their gloved index finger and thumb to widen the patient's mouth and the laryngoscope is placed in it to allow the provider to visualize the patient's glottic opening. This enables placement of the endotracheal tube, which will supply the patient with oxygen and anesthetic gasses during mechanical ventilation. The endotracheal tube is stabilized, and the laryngoscope is removed. The breathing circuit is disconnected from the oxygen mask and attached to the endotracheal tube. Afterward, the patient's vitals are checked using the monitor and the correct placement of the breathing tube is confirmed by the stethoscope. Lastly, the endotracheal tube is taped to the patient, the gloves come off, and hands are cleansed. Hand hygiene is maintained during this process by using multiple layers of gloves, which are added and removed as needed, and periodic hand cleanings with sanitizer. Practitioners are also expected to wipe down equipment with sterilizing cleanser after use.

Induction is a fast procedure that involves multiple steps and interactions between physicians, advanced practice providers, nurses, and anesthetic tools. Due to hand hygiene, this procedure is generally recognized as potentially high-risk for HAIs. It involves significant interaction between the practitioners' hands, the patient's mouth, and multiple pieces of OR equipment. Studies found evidence of pathogenic content on anesthesiology practitioners' hands around induction procedures [1]. Despite safety guidelines, infection control during anesthesia induction remains a concern. This is mainly because the fast-paced nature of anesthesia induction can lead to mistakes, such as foregoing certain hand hygiene steps. Multiple people can also be involved in the process, each interacting with the patient and different pieces of equipment at different stages. This complexity has made it difficult to isolate exactly where HAIs could originate in this process.

B. Formal Methods

In other domains where complexity can lead to system problems, such as computer science, researchers have developed formal methods. Formal methods are mathematically rigorous tools and techniques for modeling, specifying, and verifying systems [3]. That is, mathematically describing the complex interactions that define system behavior, asserting properties about the system (such as safety conditions always holding), and mathematically proving whether those properties are ever violated. Model checking is an automated, software-based approach to formal verification [4]. In this, models of a system are rendered as concurrent state machines, temporal or other modal logics describe properties to be proven, and verification occurs using highly optimized exhaustive search. In this way, model checking can prove whether a property is true. If it is not, then the model checker will produce a counterexample: a trace through the model that shows exactly how the property was violated. The analyst can use this to understand the identified problem and explore potential corrective actions.

Formal methods have traditionally been used to analyze computer hardware and software. However, an increasing body of work has shown that they can be useful for evaluating human interactions with complex systems [5], [6]. Specifically, researchers can describe how humans and the systems normally interact and prove if this ever produces problems. Such analyses can also explore the potential impact of off-normal or erroneous human behavior. Such methods have been used to evaluate and improve the engineering of many safety-critical systems, including medical devices [7], [8], airplane avionics [9], [10], military equipment [11], nuclear reactors [12], pharmacy prescription processes [13], [14], hospital workflows [15], air traffic control procedures [16], and desktop software applications [17], [18]. Despite these successes, anesthesiology hand hygiene is a unique problem space due to the need to account for the cleanliness of multiple pairs of hands and layers of gloves as they interact with items in the operating room.

C. A Formal Method for Evaluating Anesthesiology Induction

To address this problem, Rose, Bolton, and Miller [19] developed a formal method for model-checking anesthesiology induction procedures. Analysts observe anesthesia induction processes using this method and then model them in a spreadsheet. This spreadsheet identifies all the objects in the environment and whether they start "clean" or "dirty." It also tracks each person's actions/steps in the normative performance of the procedure. This specifically describes every object touched and/or touched by other objects. It also tracks the actions performed that change the state of the anesthesia providers' hands. This includes actions for cleaning them with hand sanitizer and adding and removing layers of gloves. Logical operators can be specified in the spreadsheet to indicate when there is nondeterminism (choice) in which hands are used (left, right, or both) and which person performs the step.

The spreadsheet is interpreted by an automated translation program (written in Python), which converts the contained procedure into a formal model (using the language of PRISM [20]). The produced formal model encapsulates all the different ways the procedure can be performed while dynamically tracking all modeled objects' states (clean or dirty). This includes healthcare workers' hands, where hands and/or layers of gloves (if worn) can be clean or dirty. That is, anything that is clean (including hands or gloves) becomes dirty if it touches something dirty. Gloved or ungloved hands that are dirty can become clean if a step specifies hand cleansing.

This method was used to model the normative procedure used by the Auckland Hospital in New Zealand, based on a video they published on YouTube.[1] The produced model was then model checked to ensure that all objects that needed to

[1]https://www.youtube.com/watch?v=0bEXm1Ug3Dc

remain clean always stayed clean. In particular, the model checker verified multiple temporal logic properties of the form

$$\mathsf{AG}(Object \boxminus Dirty), \tag{1}$$

for each object that needed to stay clean. That is, for all (A) paths through the model, it should globally (G) be true that the object that should stay clean is not Dirty. These analyses did not reveal any problems with the procedure [19].

III. Objectives

While the hand hygiene analysis method [19] was powerful, it had important limitations: (1) it did not account for how infection could spread between a given professional's hands; (2) it assumed that all the procedures were performed completely; (3) it did not account for potential problems that could arise due to improper cleaning between surgeries; and (4) it analyzed a procedure from a foreign hospital. The research presented in this paper sought to address all of these deficiencies.

For (1), we sought to introduce an additional source of non-determinism to account for healthcare professionals touching their hands together between steps. For (2), we intended to identify the effect of professionals skipping critical steps in the procedure. For issue (3), we extended analyses to account for objects that may not be cleaned between operations. Finally, for (4), we sought to evaluate the induction procedures used at a US medical center.

IV. Methods

A. Observation of Anesthesia Induction

We conducted a series of observations to understand, model, and evaluate the anesthesia induction procedure used at a a large, mid-Atlantic, academic medical center [(4) from our objectives]. These observations occurred in person at the medical center and through a video documenting their protocol. During these observations, our team recorded each step where the practitioners interacted with the patient, equipment, and all other environmental elements. In particular, we documented which hand was used by practitioners to interact with different elements of the operating room, as well as what equipment touched other equipment.

B. Procedure Modeling

The observations were documented in an Excel spreadsheet. This specifically identified each practitioner nominally participating in the induction procedure (there are typically two at the observed medical center) and all the objects practitioners interacted with during the procedure. Every object and practitioners' hands were assigned initial clean or dirty conditions based on consultation with anesthesiology experts. Then, each step of the procedure documented what objects were touched by other objects (including which hands touched which objects) or noted actions that would change the hands' state (such as cleaning them with sanitizer or adding or removing layers of gloves). The final model contained 76 steps executed by two practitioners, who interacted with 25 different items in the OR (including the patient and the patient's mouth).

This normative description of the induction protocol was then translated into the input language of the PRISM model checker using the tool created by Rose, Bolton, and Miller [19]. This resulted in a *normative* formal model. Next, based on consultations with our subject matter expert, CRNA (and coauthor) Michael A. Miller, we constructed properties of the form shown in Eq. (1). These specified that critical items in the OR never got dirty. This included the port, where medications were connected to the IV, the IV itself, and a cap to cover the port when it was not used.

Next, to address items (1)–(3) from our objectives, we created multiple base model variants. These models enabled formal verification analyses to expose the impact of additional sources of non-determinism and procedural non-compliance. First, we created a variant of the *normative* model that allowed practitioners to touch their hands together between each step. This *touching* model thus allowed for the potential spread of infectious agents between a practitioner's hands, which we hypothesized could facilitate spread around the OR. Second, we created multiple versions of the base *touching* model that deliberately skipped each hand hygiene-related step (i.e., cleaning hands or removing gloves). These *skip* models allowed us to assess the criticality of each hygiene step to overall infection spread. Finally, based on consultation with our subject-matter expert about cleaning practices in the OR, we constructed multiple variations of the *touching* model that accounted for objects not being cleaned between operations. In these *housekeeping* models, we identified that it was standard procedure for practitioners to clean the Pyxis drawer (the drawer where equipment such as the oropharyngeal airway are stored) and the tray (a metal tray used for temporary equipment storage next to the patient). Thus, to allow analyses to identify which of these items' cleanliness was critical to preventing the spread of infection, we created a variation of the *touching* model in which each item started dirty instead of clean. This allowed us to observe how an infection could spread between patients due to a failure of cleaning protocol.

C. Formal Analyses

We used PRISM's symbolic model checking capacities with the specification property patter from Eq. (1) to verify that equipment that should always remain clean, stayed clean (the port, the IV, and the port Caps) for all model variants. We also used PRISM's path generating capabilities for all the models to create representative traces through them. This allowed us to see how the procedures were generally performed and how infectious agents spread around the OR even without a violation of a specification. We visualized all model checker traces to identify when and how infection spread between objects. All analyses were performed on a Windows laptop with an Intel i7-13800H processor and 64 gigabytes of RAM.

V. Results

Our analyses of both the *normative* and *touching* models did not reveal anything unexpected getting dirty. The close examination of the traces showed that the objects that did get

dirty all did so when they were normatively expected to. This indicated that the evaluated normative induction procedure was safe and robust for practitioners who touched (or did not touch) their hands together. Similar results were observed when the *skip* models were evaluated. This suggests the UVA procedure is very well-designed. Effectively isolating problems, such as skipping any individual hygiene step, prevents bacterial contamination from spreading around the OR during the induction procedure. Verification results for the *housekeeping* models also did not result in anything unexpected becoming dirty. However, when we examined the traces for these models, we discovered that either the tray or the Pyxis drawer starting dirty resulted in the oropharyngeal airway becoming dirty earlier in the process than occurred normatively: before it is placed in the patient's mouth. Thus, we walked through both examples to determine what was happening (both traces are illustrated in Fig. 1).

If the tray starts dirty (Fig. 1(a)), one of the practitioners (practitioner 1) sets the oropharyngeal airway on the tray, potentially contaminating it with a previous patient's bacteria. Then the other practitioner (practitioner 2) picks up the now contaminated oropharyngeal airway and places it in the patient's mouth (potentially allowing for infection from the previous patient). Practitioner 2 picking up the oxygen mask (potentially contaminating it) and placing it on the patient further increases the potential for contamination. Practitioner 2 then picks up, and thus contaminates, the laryngoscope and endotracheal tube. These are also placed in the patient's mouth, increasing the chance of cross-patient infection.

The infection vector for the Pyxis drawer (Fig. 1(b)) is similar but more indirect. If the Pyxis drawer is not cleaned properly after a procedure, at the start of the next procedure, practitioner 1 gets their hands dirty with the previous patient's bacteria when they open the drawer. Then, when practitioner 1 picks up the oropharyngeal airway, they contaminate it and set it on the tray. This thus allows both the oropharyngeal airway and the tray to be contaminated with the previous persons' bacteria. The cross-contamination events then proceeds in the same way as the one for the tray.

VI. Discussion

In this project, we accomplished all the research objectives described in Section III. For (1), we added the ability to account for infectious agents that non-deterministically spread between anesthesia providers' hands between official procedure steps. For (2), we created variants of formal induction procedure models that skipped potentially critical hand hygiene steps to enable analyses to identify which (if any) is critical to preventing infection spread. For (3), we also created model variants that accounted for objects not being cleaned between operations, enabling analyses to explore how this could produce cross-contamination between patients. Finally, for (4), we used the original method along with the totality of the contributions associated with (1)–(3) to evaluate the potential for the spread of infectious agents through the induction procedure used at a real medical center.

In achieving this last objective, we made several significant findings. First, our results suggest that the normative induction procedure used at this medical center is remarkably robust. Specifically, the procedure was such that it prevented the spread of infection within the normative procedure, even if anesthesia providers touched their hands together between steps and/or skipped up to one hygiene step. This is a compelling result because it suggests that strict hand hygiene during the induction procedure may not significantly reduce the occurrence of HAIs. Additionally, our results suggest that ensuring the cleanliness of equipment and objects that persist in the OR between patients, specifically the tray and Pyxis drawer, is critical to mitigating HAIs (at least for the examined procedure). Thus, a potential method for reducing the incidents of HAIs would be to institute protocols that ensure equipment is cleaned both before and after an operation (especially the tray and Pyxis drawer). Other potential interventions could involve anesthesia provider training and/or the institution of housekeeping procedures between surgeries independent of the anesthesiology process.

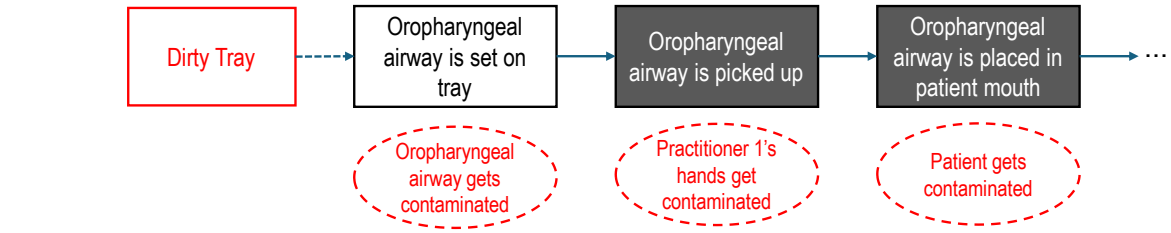
It is important to note that these recommendations are tentative. Future work should seek to validate our findings in the medical center to ensure that the identified contamination sequences can occur and that the interventions we suggest will be effective. Beyond this, there are several ways that the analysis method could be applied and extended to improve its impact. The following subsections explore these.

A. Improving Model Result Interpretability

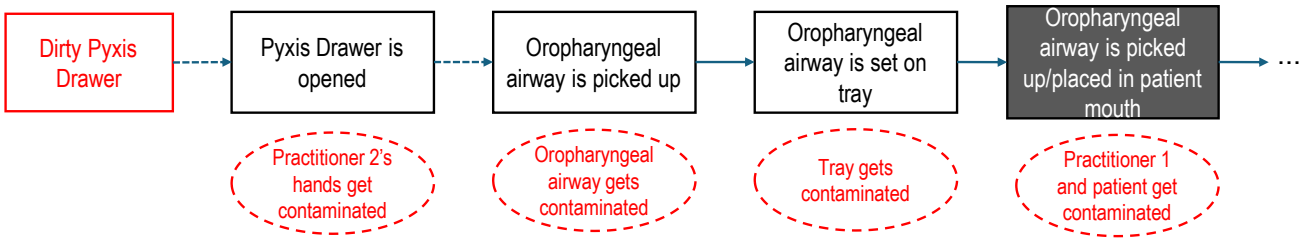
A key limitation of the model that became apparent when analyzing the results was that it was difficult to track multiple sources of infection. This was because items were either clean, dirty, or (in the case of gloves) off at any given step. This meant there was no clear differentiation between infectious agents that originated from a previous patient or a current one. As such, we could only identify the cross-patient contamination by first noticing equipment becoming dirty earlier than normatively and then manually traversing each step of the model. Future work should add the ability to keep track of all potential sources of infection throughout the formal model to aid analysts in interpreting results.

B. Additional Procedural Considerations

While realistic in the normative case, the procedure evaluated here does not capture the full breadth of induction procedures at the considered medical center or otherwise. Future work should explore different versions of the procedure from different medical environments and institutions and additional sources of nondeterminism. Induction procedures can involve additional people, which can introduce nondeterminism, as individuals' roles can be dynamically reassigned based on how a procedure evolves. This is especially true of teaching hospitals, where residents are trained by a supervisor who may need to take over or assist in specific tasks if the resident is experiencing difficulty. Furthermore, the analyses presented in this paper stopped at the end of the induction procedure. It is possible that subsequent actions (e.g., if practitioners fail to properly



(a)



(b)

Fig. 1: Patient contamination pathways from (a) dirty tray and (b) dirty Pyxis drawer. White boxes with black borders indicate steps performed by practitioner 1, and gray boxes for steps performed by practitioner 2. Solid line arrows indicate sequential steps in the process. Dotted arrows imply that sequential steps exist between connected events.

clean their hands at the end of the procedure) could contribute to infectious agent spread. Future work should extend analyses to account for this possibility.

C. Accounting for Probabilities

A weakness of symbolic model checking (like what was used for our verifications) is that it explores every possible outcome regardless of its likelihood. This is because symbolic model checking does not account for probabilities. However, the PRISM model checker does allow these to be included [20]. Thus, future work should determine how probabilities could be realistically accounted for in formal induction procedure models. This would allow analysts to predict the relative likelihood of different contamination vectors occurring, enabling proper risk analysis and the prioritization of interventions.

D. Assessing Method Scalability

Another limitation of all model-checking analyses is scalability. Model checking suffers from a combinatorial explosion (sometimes called the state explosion problem) [4]. Adding concurrent elements to a model increases the state space size exponentially. This can quickly lead to a situation where a model is too big or takes too long to verify. Our results suggest that the anesthesiology induction procedure is of a small enough scope to prevent scalability from becoming an issue (verifications took less than 0.001 seconds on average). However, this may not be the case for more complex procedures or those that extend beyond the confines of induction. Thus, future work should investigate how the method scales and, if necessary, ways of improving scalability without compromising model validity.

VII. Conclusions

This study used formal verifications to investigate how HAIs could spread around the OR from the anesthesia induction procedure used at a major medical center. It made several important discoveries. First, the absence of certain hand cleansing steps does not directly lead to the contamination of critical equipment. This suggests that the center's procedure is well-designed to prevent infection spread. Second, the failure to properly clean persistent equipment in the OR between patients, particularly the tray and the Pyxis drawer, led to several infection vectors. Thus, we recommend housekeeping protocols that will help ensure this equipment is always cleaned between operations. Future work will continue to enhance the formal analysis method so that it can be used to improve the safety of anesthesia induction processes worldwide.

Acknowledgments

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Glossary

bag/mask ventilate
: A method of ventilating a patient by manually squeezing a self-inflating bag to deliver oxygen-rich air into patient lungs from a face mask.

endotracheal tube
: A flexible plastic tube that's inserted into the trachea through the mouth or nose to maintain an open airway, especially to deliver oxygen or anesthesia to the lungs.

glottic opening
: The opening between the larynx's vocal cords through which air passes during breathing.

laryngoscope
: A medical device for examining the inside of the larynx. It usually has a light and occasionally a video camera for visualization.

oropharyngeal airway
: A medical device used in airway management to maintain or open a patient's airway. It prevents the tongue from covering the epiglottis, which could obstruct breathing.

paralytics
: Muscle relaxants used to prevent muscle movement.

preoxygenation
: A medical procedure designed to increase the reserves of oxygen in a patient's lungs before anesthesia induction.

Pyxis drawer
: A drawer in a Pyxis machine used to store medical equipment in the OR.

sedatives
: Drugs used to induce calm or sleep.

tray
: A flat, open container that is typically made from steel that protects and organizes surgical tools while facilitating easy sterilization, storage, and handling. A tray generally sits next to the patient.

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