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The embodiment of practice thresholds: from standardization to stabilization in surgical education

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Abstract
Surgeons practice their own variations on a procedure. Residents experience shifting thresholds between variations that one surgeon holds firmly as principle and another takes more lightly as preference. Such variability has implications for surgical education, but the impact is not well understood. This is a critical problem to investigate as programs seek to define procedures for competency-based medical education (CBME) and improve learning through deliberate practice. Our study analyzes the emergence of procedural variation in an early-adopter CBME program through a situational analysis of tonsillectomy, a foundation level procedure in this otolaryngology, head and neck surgical program. An earlier phase of the study identified frequent variations (n = 12) on tonsillectomy among co-located surgeons who routinely perform this procedure (n = 6). In the phase reported here we interviewed these surgeons (n = 4) and residents at different stages of training (n = 3) about their experiences of these variations to map the relations of contributing social and material actors. Our results show that even a basic procedure resists standardization. This study contributes a sociomaterial grounded theory of surgical practice as an embodied response to conditions materialized by intra-relations of human and more-than-human actors. Shifting root metaphors about practice in surgical education from standardization to stabilization can help residents achieve stable-for-now embodiments of performance as their practice thresholds continue to emerge.

Keywords Competency-based medical education · Embodiment · Procedural variation · Situational analysis · Sociomaterial practice · Surgical education

Introduction

There are differences in the ways surgeons perform the same procedure that do not rise to a level of concern for patient outcomes. The consequences for residents are another matter, however. Residents experience shifting thresholds between variations that one surgeon might hold firmly as principle and another take more lightly as preference

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(Apramian et al. 2015a). This means that when residents walk out of one operating room and into another, they are not just switching rooms, they are switching practices. In some cases, if they don't perform a procedure exactly a particular surgeon's way, they report consequences such as being reprimanded, taken off the case, or receiving poor performance appraisals (Apramian et al. 2016a).

What should be done about shifting thresholds of practice? Surgeons' responses to this phenomenon tend to fall into two camps: *standards* and *innovation*. In the first camp, the response is to eliminate variation by setting procedural standards. If the threshold line for practice is actually more like a high jump bar, set at a predictable level, so the argument goes, then learning will be accelerated. Residents can engage in deliberate practice, and surgeons can offer focused feedback. The only variable that remains will be individual performance: the time it takes each resident to master a standard (Nousiainen et al. 2018). These assumptions about learning and formative assessment are part of the narrative about competency-based medical education (CBME, Frank et al. 2010).

While some approaches to standardized performance may accelerate learning (Ericsson 2004; Nousiainen et al. 2018; Szasz et al. 2015) the innovation camp questions whether they *improve* learning (Pusic et al. 2018). In studies of surgical practice, surgeons agree that being able to adapt one's approach in response to changing conditions is essential (Apramian et al. 2016b; Pope 2002; Svensson et al. 2009). And these surgeon's intuitions are also part of the master narrative about CBME: that competency is adaptive expertise emerging in response to a dynamic interplay of complex conditions (Bates et al. 2019; Fraser and Greenhalgh 2001; ten Cate et al. 2010).

We contend that responses falling into the standards camp or the innovation camp are over-simplifications because they reduce procedural variation to these binaries: a problem for learning, or an essential feature of practice. In fact, they go hand in hand. Arguably the biggest roadblock to improving surgical learning is that previous research has not fully explored the conditionality of practice. Indeed, ten Cate et al. (2010) identified practice conditionality as *the* general problem for medical education: gaps in our understanding of the situations through which practice emerges. One of the reasons for this gap is the assumption that practice emerges through only social processes (Goldszmidt 2017; Fenwick 2014; Mol 2002). This assumption is called into question by sociomaterial theories of practice which show how material, spatial and temporal agencies such as tools and technologies, use of space, and economies of time and money act both with and on social actors (Fenwick et al. 2012).

We argue that a sociomaterial study of procedural variation contributes a more complex understanding of how surgeons learn and practice surgical procedures. This study deploys a situational analysis (Clarke 2003) of variations in the procedure of tonsillectomy to ask, how do sociomaterial actors materialize different practice thresholds?

Methodology

Presenting our methods as "methodology" signals that methods are based in ontological and epistemological assumptions about what we research and how to understand it. Situational analysis (SA) is a sociomaterial approach to grounded theory which accounts for more than human actors in the study of practice (Clarke 2003; Clarke et al. 2015).

Situational analysis as grounded theory

Grounded theories are constructed by the core methods of open coding of data to identify types of action, multiple analytic exercises to explore the processes producing these actions, further data sampling to explore emerging theory, and completion of the theoretical model at the point of sufficiency, when discrepancies are accounted for and no new insights generated (Apramian et al. 2017; Charmaz 2006; Clarke 2003). All of this theory-building work assumes human actors. SA innovates at the open coding, data sampling and analysis levels by identifying hidden actors and exploring their relationships to the more visible actors in a case through situational maps. Hidden actors are human or other space/time/material actors which are implicated in the data. While they may play key roles in conditioning a situation, the effects of hidden actors are often silent (or silenced), and therefore not well understood (Clarke et al. 2015).

Situational analysis as sociomaterial theory: interaction and intra-action

The term "situational analysis" can be confused with certain assumptions about situated practice. Theorists of situated cognition, for example, recognize that environments and artifacts affect learning (Schwartz et al. 2005). Situated cognition emphasizes the importance of context and interaction in what we learn and how we learn but takes the context and the knowing human to be matters of fact (Clarke et al. 2015). It is not that notions of context and interaction are necessarily incorrect or unimportant, but they are incomplete. Sociomaterial studies of practice make three analytical moves beyond situated cognition: they study the makings of context itself as a situated practice, they study the agency of space, time, and material in practice, and they take the boundaries between human and more than human actors to be contingent effects of practice. Suchman, following Barad (2003), describes the sociomaterial shift in her own analysis of situated practice as a move from studying interaction between humans and machines (Suchman 1987), to mutually constitutive "intra-action" (Suchman 2007, p. 267).

Sociomaterial theories of practice, first developed in sociological (Hirschauer 1991; Latour and Woolgar 1979) and philosophical (Haraway 1988) studies of science and technology, emphasize that practice is assembled (Latour 2005) through contingent and dynamic relations between social, spatial, temporal, and material actors, and that the very nature of what counts as social and material is therefore unstable and emergent (Haraway 1991; Barad 2003). We use Latour's term 'assemblage' to describe an intra-relation of actors in practice, and Barad's theorization of how actors emerge through intra-action using the verb "materialize" (Barad 2007, p. 274). Why add such complex considerations to the study of medical education? Because we participate in making what we know, and that has profound material consequences (Mol 2002).

Situational mapping

In Clarke's words, "a situational map should include all analytically pertinent human and nonhuman, material and symbolic/discursive elements of a particular situation as framed by those in it and by the analyst" (Clarke 2003, p. 561). Once these elements are identified, the analyst engages in visual thinking, circling elements on the map and linking them with others to specify "the nature of the relationship by describing the nature of that line" (p. 569). This is purposely messy work because it is meant to elucidate complexity by

visualizing hidden actors and interrogating the data in fresh ways. A visual model might be the outcome, but mapping can simply be a roadmap for analysis. Questions include: "What seems present but unarticulated?" And, how do the nonhuman actors "condition the interactions within the situation through their specific properties and requirements—the demands they place on humans?" (Clarke 2003, p. 561). Although mess is the nature of complex practice, it can be illuminated through a ground up approach to theoretical sampling and analysis:

> With your map many, many times—tinkered, added, deleted, reorganized… You can talk at some length about every entry and about its relations to (many if not most) other entries… You think these are the most important elements. (Of course, there are many others, but they don't seem to 'make a difference' to the stories you would tell about the situation (Clarke 2003, p. 571).

What stories could we tell about this situation? All knowledge is situated and therefore partial (Haraway 1988; Clarke 2003). Therefore, it is important to stake out our own positions as a research team to give readers a map for understanding how far to travel with these findings (Law 2004)—in other words, how similar their stake in the game may be. "We" are an interdisciplinary group with multiple identities: physicians, social scientists, teachers, qualitative researchers, experts in medical education. We are pursuing research programs to study the effects of CBME.

Participants and data sources

The choice to study the situation of tonsillectomy came through a program of research with a mid-sized otolaryngology-head and neck surgical program in Ontario, Canada which is an early adopter of CBME. This program has developed criteria for assessing competency by defining procedures as entrustable professional activities (EPAs) and is engaged in an ongoing review of this process with the Royal College of Physicians and Surgeons. Since tonsillectomy is considered a basic procedure with few acknowledged variations (Messner 2005), the program recommended it as a manageable, introductory case to explore the effects of procedural variation on teaching, learning, and assessment.

Tonsils and tonsillectomy

Messner (2005) categorizes tonsillectomy into two classes of procedures, extracapsular and intracapsular, with associated instruments (knife, cautery and laser) and techniques (dissection and ablation). The surgeons in our study most frequently perform extracapsular tonsillectomies with monopoloar or bipolar electrocautery instruments. Figure 1, Extracapsular tonsillectomy (from Messner 2005, p. 225) illustrates a common technique using monopolar cautery to dissect the tonsil capsule from the plane of the pharyngeal musculature, cutting from the superior to inferior pole. Essentially, tonsillectomy is a simple matter of removing and cauterizing these small bits of tissue on both sides of the palate to complete hemostasis. In one of our intraoperative observations, a surgeon performed a tonsillectomy in under 15 min. With junior residents, the procedure was up to twice as long. Some of the surgeons who joined this study were interested in Ericsson's (2004) theory of deliberate practice and wondered if more insight into key variations might lead, if not to standard ways of operating, at least to efficiencies in learning.

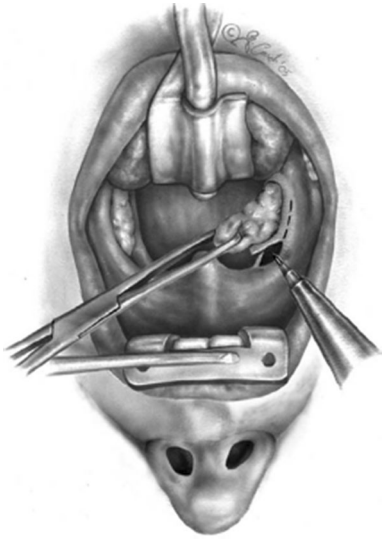

Fig. 1 Extracapsular tonsillectomy

Theoretical sampling

The theory of the embodiment of practice thresholds described in this paper results from a deep dive into a small set of interviews with surgeons and residents about different principles and preferences in their experience of performing tonsillectomy (n = 7, average length of interviews, n = 40 min). Sociomaterial research, because it studies particularity, uses small units of study for an in-depth analysis of actors and relations (Latour 2005). And like other grounded theory research, situational analysis is an iterative approach to constructing theory by beginning with initial data sources and progressively asking more refined questions through the process of theoretical sampling (Apramian et al. 2017).

The number of interviewees was bounded by the situation of study, but the interviews were informed by earlier phases of the study which we describe briefly below, but report in detail elsewhere (Apramian et al. in review). Data sources and preliminary results for the study are summarized in Table 1, Tonsillectomy Situational Analysis.

In phase one and two, we were surprised by the number of variations in a 'basic' procedure. Starting with textbook variations on tonsillectomy (Bailey et al. 2006; Lee and Toh 2007; Mochloulis et al. 2014; Myers 2008), one member of the research team (TA) analyzed the tonsillectomy operative notes of the surgeons in the study who routinely perform this procedure to identify if these variations were present, and through open coding identified many more. In the focused coding phase, TA conducted intraoperative observations of tonsillectomy procedure days to document this surgical program's most frequent variations on tonsillectomy. A full report on the methods and results of these phases of the study is forthcoming (Apramian et al. in review). We could not get to a robust understanding of the actors and relations in variations on tonsillectomy or analyze how these practice thresholds emerged without the earlier phases to identify variations, but they are not the story here. The work of this theory is not to help surgeons choose better principles or upvote more frequent preferences, but to help educators understand how practice thresholds materialize.

For the present phase of the study, MO engaged in semi-structured, dialogical interviews (Frank 2005) with surgeons (4 of the 6 participants from phase one due to parental leave),

Table 1 Tonsillectomy situational analysis

Phase	Data sources	Preliminary results
Open coding: variations on tonsillectomy	Surgical textbooks (n = 4) Operative notes (n = 67)	Possible variations (n = 47)
Focused coding: intraoperative observations to document frequency of variations	Surgeons routinely performing tonsillectomy (n = 6) for a total of (n = 7) tonsillectomy operating days	Most frequent variations (n = 12)
Theoretical sampling: Interviews with surgeons and residents about most frequent variations to identify actors and relations	Surgeons (n = 4) Residents (n = 3)	Analytic maps of actors and relations in tonsillectomies

using the frequent variation data to probe the rationale for their tonsillectomy threshold: defined as the line between their principles and preferences in the procedure (Apramian et al. 2016a, b). Residents on a continuum of achieving the tonsillectomy EPA (in program years 2 and 3 of the residency) also consented to participate in interviews about their experiences learning these different practice thresholds and their own emerging preferences (n = 3). A dialogical approach to interviewing seeks to give participants opportunities to narrate their perspectives, then puts these voices into conversation with each other to provide a rich picture of meaning-making (Frank 2005). The work of revealing silent and hidden actors in these conversations was engaged through analytic mapping.

Analysis

MO developed the analytic maps of tonsillectomy variation through open coding of the interviews as they occurred, highlighting portions of the transcripts that discussed variation in order to make tentative connections from the variations to other human and nonhuman agencies she considered likely to be analytically pertinent, such as references to patients, anesthetists, nurses, time and cost constraints, spatial positioning, and surgical instruments. The maps were iteratively refined in three ways.

First, they acted as sampling devices, as each interview added further actors and connections to the maps which raised more questions. For example, the data suggested a relationship between surgeons and instruments, which MO pursued using the sensitizing concept of *embodiment* as the interviews progressed. The concept of embodiment is a rich and contested site of inquiry in many disciplines (for example, in quantum physics, Barad 2012; in cognitive science, Moya 2014; in multimodal semiotics, Streeck 2013), highly influenced by Merleau-Ponty's (1960) phenomenology of perception: We respond to the world through embodied habits of being, and we are also always becoming embodied through sensory engagement with the world. The question for a situational analyst is *how* embodiment materializes in *this* situation. Sensitizing concepts require a light touch, or they do the work of theorizing without this grounding (Latour 2005). Our starting point for embodiment comes from a reference source on the multimodality of practice. Here, embodiment is defined simply as the idea that practices "are produced through the human body in its material form, the nature of the practices being, in large part, contingent on the forms, practices, and plasticity of the human body" (Glossary of Multimodal Terms, n.d.).

Second, the maps formed the basis of analytic discussions with other members of the research team (LL, KR, SC). For instance, a tentative idea about how surgeons perform with/as instruments, enriched with data and analysis, became part of our concept of embodied practice which resonated with the surgical program when we shared this idea with them.

Finally, MO and TA worked with a professional medical illustrator (Kryskimedia.ca) to further clarify the relationship between the findings of this study to the shifting practice thresholds identified through earlier studies. We share the final visual concept in the results section to illustrate our theory of the embodiment of surgical practice thresholds.

Results

Our initial concept of the threshold line was a straight one, albeit dotted, to illustrate its illusory character for a resident seeking to discern the line between a surgeon's tightly held principles and looser set of preferences in their procedural approach. This *theory*

of thresholds of principles and preferences is grounded in observations and interviews about variation across a wide sample of surgical procedures (Apramian et al. 2015a, b, 2016b). But the tonsillectomy study affords a detailed analysis of variation in one procedure. In Fig. 2, Embodied Practice Thresholds, we see on close up inspection the threshold line between a surgeon's principles and preferences becomes illusory and wavy, not only for residents but also for surgeons, as it weaves around and through instances of embodied performance. There are three reasons for this instability which are labelled for reference to the illustration: (A) embodiment as the condensation of preference, (B) embodiment as an assemblage of sociomaterial actors, and (C) embodiment as a plastic practice. In what follows, we share quotes to narrate the perspectives of the surgeons and residents and explore how their experience of procedural variation led us to theorize embodied practice thresholds.

Embodiment as the condensation of preference

This section explores how the threshold line of principles to preferences varies between surgeons. Consider this quote from a resident about the differences in something as basic as how surgeons grasp the tonsil:

> The variations start literally from the very beginning… Some people will grasp it front to back, some people will grasp it top to bottom, some people say don't re-grab and some people say you always have to re-grab. (R3)

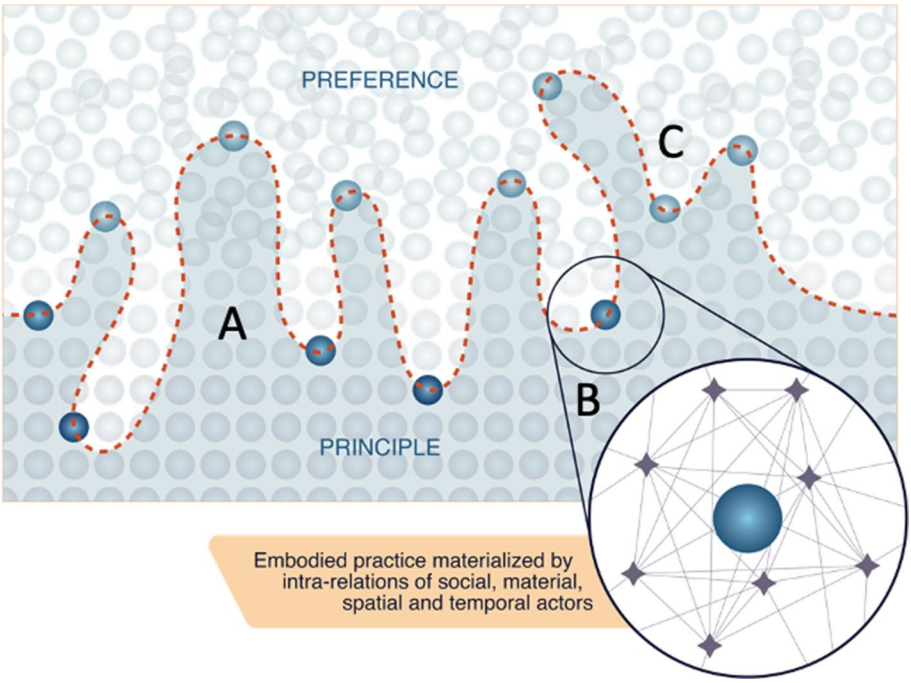

Fig. 2 Embodied practice threshold

The more tightly condensed a surgeon's habitual approach appears to be, the more it seems to be a principle, a standard way of operating: "don't regrab/always regrab." A resident in this situation must discern which standard applies to which surgeon, but these yes/no binaries are relatively simple to recognize and perform. However, sometimes surgeons don't seem to enact a binary: "Some say start cutting inferiorly, some say start superiorly, and some don't care" (R3). In this case of three alternatives, a resident not only has to figure out what 'matters' to surgeon x versus surgeon y, but also must begin to justify *why* to take a certain approach. Rather than shifting up or down between yes/no practices, the threshold line begins to wave.

If a surgeon "doesn't care" they may be recognizing that the resident is ready to start establishing their own preferred approach: "When they're first starting off, let's learn my way, until we can do it this way. Then once they're appropriately skilled, I would say, do you want to try something different" (S2). However, some surgeons view preference itself as a matter of principle: "It depends on the patient which way I like to go, but I give the residents a lot of independence so they can do whichever they like for that" (S3). And then there is the question of how much a principle really comes down to preference:

> I always tend to have a reason why I do something as most surgeons do but I'm not sure research captures this all that well, that people do things that are good for them. And so, what is safe in my hands may not be safe in another person's hands (S4).

This quote about "safe in my hands" emphasizes that a surgeon's habitual approach to a procedure is embodied, a condensation of mind/muscle practice into the experience of "my hands." This means that the threshold line is not merely a theoretical exercise for residents to discern how rigidly or loosely a surgeon performs a procedure as a set of principles or preferences; it is the embodied expression of how the surgeon *feels* the procedure. However, the threshold line not only varies between surgeons, it varies within surgeons.

Embodiment as an assemblage of sociomaterial actors

The data in this section about variance within surgeons will destabilize matters of fact about who is performing surgery. To begin, here is a 'matter of fact' from one surgeon about how his dissection approach to tonsillectomy has been embodied differently over time: "I used to be a top to bottom kind of guy, but now I'm bottom to top, and that's probably been the case for the past few years" (S4). What is the reason for this variation?

> The reason why is the bottom of the dissection is the most vascular. It's the place where you can get into the most problems and so if you identify that first you're being safer in my mind. And the exposure it's dramatic actually because you know when you're working this way, you're kind of working down into a hole to a certain extent, but you can actually release this tissue… However, a technique is only as good as what you have in front of you. (S4)

To paraphrase this surgeon, the reason for the change in his procedural method of dissecting the tonsil, now cutting from inferior to superior pole, is that cutting a tonsil out presents a set of visual-spatial problems. The pull-out detail at point B in Fig. 2 depicts an instance of embodied practice as a network of relationships assembled by sociomaterial conditions. We use the verb assemble in Latour's sense of the ongoing relations between many different agencies to materialize a phenomenon. A matter of fact is never a singularity, it is an assemblage in response to a concern (Latour 2005).

The spatial (the inferior pole of the tonsil) and material (vascular supply in the region) are related to one another and to the surgeon's intention to cut out the tonsil. The way this surgeon has experienced the relationships in this problem, "the exposure, it's dramatic" embodies his solution to avoid excessive bleeding by first identifying the most vascular region and working his dissection up from there. The mouth is a small and obstructed surgical field. The visual-spatial problem of getting at tonsillar tissue is not unique to this surgeon, but it is solved in various ways. In fact, this surgeon's visualization strategy may seem counter-intuitive to others. Surgeons 1, 2 and 5 in this study use the superior to inferior dissection approach routinely. Surgeon 1 reasons:

> The most important step in my mind is finding the plane that is the tonsil and the muscle… So, finding that can be challenging sometimes if the patients have had a bunch of infections or they've had a procedure done to drain an abscess … I usually start trying to find the superior pole of the tonsil but if that's problematic for some reason, it's scarred or it's not coming up very easily and you can see that there's a plane more inferiorly, then I will switch and go to that. (S1)

The inflamed matter of the tonsils is the primary visualization concern for Surgeon 1, assembling her embodied solution for identifying the extracapsular plane at the superior pole. On further probing in this interview, it seems this reasoned solution to dissect from the superior pole in order to easily identify the plane is further related to a startling experience early on in her career as a faculty member:

> The comment was, what's this fat? And I was like, stop right there. And we had to over-sew the muscle and monitor that patient. And yeah, so it was very instrumental in both mine and that particular resident's learning, I think, that complication, that it can happen very quickly for a simple procedure. (S1).

The experience of a resident almost cutting the carotid artery made indelible marks on Surgeon 1's feel, not only for how to perform tonsillectomy, but how to teach it. Her solution to the problem of visualization sits in marked contrast to Resident 1, however, because a different problem 'matters' for this resident: "I have found in my limited experience, the inferior pole to be easier to identify, because for the superior pole you really have to curve your hand into get to that pole" (R1).

It could be argued that Resident 1's emerging preference is just that, a pitstop of inexperience on the way to embodying an easier feel for reaching the superior pole, or a sign of the need to let go of inconsequential details on the way to a more reasoned understanding of the problem. However, Surgeon 3, who might appear to residents not to have a preference about where to begin the dissection ("some say start cutting inferiorly, some say start superiorly, and some don't care" R3), has a different rationale for the problem altogether:

> So, for an exophytic tonsil, or like an outie, I think it's really easy to start superiorly for those tonsils that are outies. And especially for the superior pole, if it's an innie, I think it's easier to start from inferiorly. It depends on the patient which way I like to go, but I give the residents a lot of independence so they can do whichever they like for that. (S3)

The spatial relation of the tonsil to other tissue is intimately related to the dissection visualization problem for surgeon 3. Innie and outie tonsils 'matter' to this surgeon, and having an embodied flexibility to handle this matter is a principle for teaching too: "so they can do whichever they like for that."

Procedural variation is not just a matter of reason, it is an embodied performance of problem-solving conditioned by an assemblage of spatial, temporal, material and social actors. Even the most gripping and steadfast justification of a principle: "I'm bottom to top… the exposure, it's dramatic" is subject to change over time and in response to changing conditions: "I used to be a top to bottom kind of guy… However, a technique is only as good as what you have in front of you" (S4). There is a temporal relation to a surgeon's threshold for a procedure as it becomes embodied differently over time, and it is not necessarily a linear progression of incorrect to correct understandings of the problems at hand, or a progression of inexperienced to experienced responses in hand. The embodied practice threshold line is wavy because it is being pushed and pulled, materialized through shifting relations between social, and more than social actors assembling problems and solutions.

The contrast in these quotes from Resident 3 and Surgeon 2 illustrate the kinds of conditional relations performing an embodied response to an agreed-upon problem.

> Once you have good exposure, that's just not technically that hard, but in my mind, having seen a lot of residents go through, they often struggle with getting the right amount of exposure. Which is a certain instrument we use, it's called a Boyle Davis Gag, of just getting it in the right spot, open the mouth up enough to do it, and not having things be asymmetrical. Again, that exposure at the beginning is, I think, the most important part. Once they could do that, everything else kind of flows naturally throughout. (S2)

> If you're fighting against the tongue the whole time, you're not going to get the best view of the tonsil on one side or the other. You risk actually injuring the tongue and then if you're constantly trying to get it out of the way then you're not paying attention to the other stuff around it. I would say getting that retractor in and suspended well is the best first step… Also, honestly, having an anesthetist who knows and who is doing tonsils all day and putting the tube in the midline. Because the tube can look like it's in the midline at the lip but if they put it down from the right, like you're constantly fighting tongue versus tube because the tube should be in the midline so you can suspend it, retractor against tube against the tongue. (R3).

Surgeon 2 is concise about the problem of visualizing the tonsils and identifies one type of material (the Boyle Davis Gag) as an important actor that the surgeon can control. The resident, however, acknowledges that she is not the only social actor performing tonsillectomy and identifies a more complex set of conditions. The mouth gag for retraction solves the problem of exposure, but conflicts with another, the problem of creating an airway. Both these materials push on another actor, the patient's tongue. If a surgeon works with an anesthetist "who knows," because they have been "doing tonsils all day," to place the endotracheal tube at the midline, the surgeon does not have to fight so hard against tongue and instruments to reach the tonsil. Problems, and embodied responses to problems, are assembled not just by the will of the surgeon, or by the conflicting intentions of the surgeon and anesthetist, but by the demands that spatial, temporal, and material relationships place on human actors. What we see in the contrast between Surgeon 2 and Resident 3's accounts of the same situation is a difference in how 'matter of fact' an embodied response becomes once the assemblage of problems is condensed to a key step. Embodied assemblages become firmly entrenched in practice once they are condensed as a preferential approach to a problem the surgeon feels some predictability

and control over. Mol (2002) describes a stable assemblage as a black box which conceals the conditional relations assembling it. In the next section, we unpack some black boxes in our data to show that embodied practice is more malleable than it appears.

Embodiment as a plastic practice

The black box of automaticity in expertise is a familiar problem in surgical education. Surgeon 1 described problems she encountered learning tonsillectomy when a faculty member black-boxed it as two steps:

> Set up, take out tonsil. Those are his steps, because he's done so many that actually, the further away you get from something, it's probably harder. The way I learned how to do tonsillectomy truly was from a senior resident. Because he was not that far away from learning… he could say, you know what, your retraction step is the problem. You need to grasp it like this, you need to pull it harder, then you're going to see that plane… and he just said, just tilt your hand a little bit differently and bring your tubing in like this so it's not getting in your way. Just those little, not even really the steps but more just little leaders, it just revolutionised how I did that procedure. (S1)

How can a sociomaterial understanding of the plasticity of surgical practice help learners unpack the black boxes of automaticity and variation? As surgeon 1 explains, knowing key steps through a procedure is important. But having different repertoire for the same step is also important. For example, some surgeons tell residents to only grasp the tonsil once, because if the indication is recurrent tonsillitis, chances are it is a scarred, inflamed bit of tissue ripe for bleeding or falling apart. On the other hand, re-grasping it once the initial cut is made has affordances for keeping the cut in plane through improved visualization: "It actually helps to show you the plane more so, because if you're only re-grasping one side you're not actually getting enough retraction, and sometimes it's easy to come off the plane" (S3). Most importantly however, it is, as Surgeon 1 suggests, the handheld plasticity "leading" into and out of the step that really matters to learners: "You need to grasp it like this, you need to pull it harder…just tilt your hand a little bit differently." Knowing *how* to orient one's body in relation to the instruments and patient's bodies is crucial knowledge for learners, which they may embody more slowly if they are not given explicit coaching. This insight from an early stage learner is instructive:

> For me, I watch the angle of their hands more so than the angle of the instruments, if that makes sense… Because there are so many ways to move the instrument this way at the distal end, but it's watching how they move their hands that I find is the most helpful, because that's the way I want to move my hands to get the end of the instrument to do that thing. (R1)

Embodied procedural approaches are plastic because they depend on the human body assembling with other instruments and bodies to act as one. In some cases, surgeons have a choice about what feels right in their hands. One surgeon told us they preferred a longer grasping instrument, because it gave a finer point to their hand in the very crowded oral surgical field. Another surgeon preferred a shorter tenaculum, finding the longer one unwieldy. Some surgeons and residents we asked weren't even aware there was a choice. Cost-savings research by another member of the surgical department at one site some time ago led to a decision to reduce instrumentation for tonsillectomies at another (S1, S4).

There is also a plasticity to the relation of surgeons acting with instruments that emerges with time.

> What I like most, and, again I think some of the staff do it differently too, the one I've seen the most commonly, the one that I like, is when you use your monopolar. You make a small cut, but then you can use your monopolar almost as, like, a spreader to find the right plane. (R2).

In Resident 2's hands, the monopolar acts as a spreading tool. She has experienced using bipolar and co-blator cautery as well for dissection, and has assembled a preferred, embodied response to the problem of identifying the plane with the monopolar. This resident is in the third year of training. Resident 1, who has just started the second year, prefers bipolar, even though she has only used it once, because it does not have this spreading action:

> I felt like I was a little bit more in control because, if that makes sense, because I felt with the monopolar it's just like … it slices through things for you which is nice, but the bipolar takes a little bit more time. And maybe just because I'm inexperienced at this point and feel like maybe I have time to second guess myself if I need to… that's what I felt the one time that I used it, talk to me in two years and I'll probably have a different answer. (R1)

As a surgeon gets more experienced, their own bodily preferences may be subsumed to more demanding problems with an apparent rationale:

> Sometimes we have a bipolar cautery on our set-up, but we only use that if we get into some bleeding or something, or for a post-tonsillectomy bleed…Or I had a patient with cochlear implant, for example, that couldn't use monopolar cautery, so I had to do it with bipolar cautery. But, traditionally, we use monopolar cautery… It's cheaper. (S3)

But sometimes, a rationale is simply cover for what I'm most experienced with, or what's been made available to me:

> [Monopolar is] the most efficient in terms of speed and it's the cheapest. And probably it's what I … well, it isn't the cheapest, actually. I guess if you wanted to use the bipolar that would be the cheapest thing to do because it's just a reusable instrument whereas the monopolar is an instrument that is a single use instrument. (S1)

Resident 1 and 2 acknowledge that preference is an assembled experience which varies with exposure to different options and in response to identified problems. Resident 1 identifies her problem as one of learning at this point, being afforded time to second guess herself. Resident 2 associates the surgical problem of finding the right plane with her preference for monopolar. Choices are also made for surgeons about the instruments in hand due to the demands of patient indications and cost-saving measures, and sometimes for no 'good reason' at all. Ultimately, a surgeon's practice threshold is an embodied, plastic assemblage for problem-solving, orienting their own bodies to the demands of patient indications, spatial positioning, material affordances, and temporal considerations.

Discussion

We began this paper with reference to a debate in surgical education: whether to set standard ways of proceeding, or to make room for innovative practice. This problem likely resonates across medical education currently, as the tension between creating opportunities for deliberate practice and practicing a complex profession goes to the core of designing CBME. We described this as a binary approach to focusing on problems of learning, or problems in practice. On the one hand, medical educators and learners alike benefit from shared constructs to guide workplace instruction and assessment (ten Cate et al. 2010; Shalhoub et al. 2014; Govaerts et al. 2011; Boulet and Durning 2018). If shared constructs were pushed to the exactitude of determining a standardized approach to a procedure, this could create efficiencies in training and claims of improved performance (Ericsson 2004). This might be a tempting scenario now that the burdens of more frequent assessment are falling on faculty shoulders. Responsibilities for teaching and entrusting standard procedures could be parceled out among faculty, and residents could spend as much time as needed developing competency per procedure.

On the other hand, surgeons recognize—and value—that an essential quality of their expertise is the ability to adapt to uncertain conditions (Apramian et al. 2015b, 2016b; Cristancho et al. 2013; Fioratou et al. 2011). Our results concur with the experiences of surgeons and empirical research about innovation in surgical practice (Cristancho et al. 2013; Pusic et al. 2018), demonstrating that even the most basic, 'two-step' procedure resists standardization. What this study adds is a theorization of the conditions for procedural variation. 'Standard' ways of proceeding in the operating room are embodied, plastic assemblages: approaches to problem solving which assemble with, around, and against other bodies. In this study, inflamed, exophytic tonsils, anesthetists, retractors and endotracheal tubes, and faster, slower, or cheaper cautery instruments are hidden actors participating in variations on the situation of tonsillectomy.

Embodying stable practice

Since it proves both impossible and undesirable to remove variability in procedures, we suggest 'stabilization' is a better metaphor for surgical learning than standardization. Stability implies a steady hand, a preferred, even principled way of doing things. Yet stability can also refer to a shifting balance in response to constant movement, as the waves of changing and sometimes unpredictable conditions push and pull on us. And stability also helps us when we have to balance competing demands. How might surgeons help residents embody stability?

While a surgeon's practice appears more stabilized, their embodied practice thresholds are emerging through inquiry too: "I used to be a top to bottom guy." Surgeons are always solving sets of problems. Cristancho and colleagues describe this work as improvisational (2013). What we see in resident operating is the problem-solving in more detail—their neural-muscular plasticity still developing with awareness of the problems at stake and multiple experiences of ways to embody solutions. The ability to improvise has been reviewed in literature on developing expertise in music, theatre, and teaching (Sawyer 2011). What this research teaches is that expert improvisation is grounded in repertoire (Ott and Hibbert 2020). A junior resident's repertoire of moves haven't been embodied as tightly yet into a condensed assemblage of sociomaterial actors which can exercise control. There are

insights from our data that suggest ways to teach repertoire for embodied practice which can respond to variable conditions. In presenting these as general suggestions, we recognize first, that some of the richness of detail is lost, and second, that the particularity of our results makes them productive in this situation but only suggestive for others. We invite readers to look from our data to their own situations and make sensible connections.

Identifying central problems to embody stable solutions

Research on learning motor skills has shown that learners can get lost in the details if they don't have a bigger picture of the goal to achieve (Wulf et al. 2010). Our study might seem to contradict this finding, because we show that the intricacy of details materializing procedural variation is an essential feature of learning surgical practice. Surgeons in our study did not always agree on procedural details, and even when they did agree, they embodied unique hand signatures for each step. However, they all identified tonsillectomy as a problem of visualization.

In our study, visualization of the tonsil extracapsular plane was a central problem. We might draw on a musical metaphor to say that visualization is the theme of tonsillectomy, and what happens is a variation. Having a thematic hook for a procedure may help ground residents, providing a stable goal for rehearsing multiple variations. This should be a consideration when designing EPAs. The idea of a link between cognitive representation and motor performance has been extensively studied in a variety of disciplines (Schuster et al. 2011), theorized as an equivalency of neural simulation of action to physical action through fMRI studies (Jeannerod 2001), and supported by a review of research on the positive effects of mental rehearsal in surgical education (Wallace et al. 2017).

Establishing spatial repertoire

Assemblages create *relational space*, which is not space in the sense of a container or a metaphor for social interactions. Relational space in a topographical sense refers to the way that relations between actors make space (Mol and Law 1994). Helping residents recognize the demands and affordances that different instruments and spatial orientations place on their bodies establishes spatial repertoire: room to maneuver within a procedural assemblage. Stories such as the one by resident 2 about how the monopolar becomes a spreader in her hands, or the quote by resident 1 about observing the joint between a surgeon's hands and the instrument, illustrate how embodied performance is an assemblage of spatially oriented actors. Surgeons can share their own stories about their preferences, giving residents social as well as spatial repertoire for understanding that they come to embody different approaches for solving problems.

However, we do not suggest that learning that practice is uniquely embodied means anything goes. To paraphrase Bruno Latour, while procedural variation exposes "that reality, unity and indisputability are not one and the same, this has nothing to do with interpretive flexibility" (Latour 2005, p. 116). Surgical variations are responses to problems, and problems are not just matters of interpretative definition or personal experience, they are assembled with other actors. In 2010, the consensus on CBME initiatied by the Royal College of Canada anticipated that one of the ways to reform medical education was to perform task analyses (Frank et al. 2010). Our experience understanding variations in the skill set of performing tonsillectomy suggest a more nuanced approach to task analysis is to identify 'big picture' problems contingent on sometimes overlooked social and material actors.

For instance, understanding that the problem of tonsillectomy is visualization and how the Boyle Davis gag and the anesthetist are key actors in this assemblage may help residents to see the forest through the trees of variable approaches to this problem. This concurs with the research of Wulf et al. (2010) on the importance of higher order thinking in mastering motor tasks.

Practice as learning

Finally, if we accept that surgery is situated practice, that surgical procedures are multiple, plastic, embodied responses to problems, then we accept this implication: situated practice *is* learning-in-practice. There is no learning/practice binary. The literature on cognitive research in learning tells us there are three roads to developing expertise: rote rehearsal leads to limited forms of expertise without understanding, meta-cognitive reflection allows us to learn from and adapt our expertise, but only alertness to putting things together in new ways leads to innovative practice (Perkins 2008). A more than competent surgeon—an expert one—must retain the ability to learn if they are going to push past automaticity (Ericsson 2004). As much as Ericsson's views on deliberate practice have appeal for CBME, however, they contain assumptions about expert performance which need critique.

The theory that practice time equates with proficiency has become a common sense notion, but is debunked by meta-analyses which show that deliberate practice accounts for less than 20% of the variance in average performance across the fields of music, sports, and chess, and explains a mere 1% of the variance at elite levels of performance (Macnamara et al. 2016). A close reading of earlier expertise studies promoted by Ericsson (2004) may explain why. They tend to focus on the practice of singular skills under controlled conditions with few actors. As complex as mastery of the game of chess or the performance of a concert pianist may be, these are far more predictable, rule-based situations than a surgical procedure. The difference between practicing for a performance and practicing a profession cannot be overemphasized.

If we are going to adopt a musical metaphor for expertise in medical practice, perhaps a better one is jazz (Miller et al. 2001). An expert surgeon can improvise because they have embodied a repertoire for responding in ensemble. Our study shows that there are hidden actors *dis-assembling* a surgeon's embodied control as well as assembling it, which is why a surgeon's practice threshold remains an unstable, wavy line. This complexity is intensified by the phenomenon that actors do not need to be local and immediate to have agency in a situation (Latour 2005; Mol and Law 1994). For instance, cost-saving measures in this study's situation assembled embodied approaches to surgeon's preferences for instruments long after and some distance from the site of the original decision point. This lends further credence to the critical role that opportunities for reflection-in-practice and experiencing the unexpected play in designing learning in medical education generally (Eva and Regehr 2005).

Conclusion

Bates et al. (2019) argue that while standardization has many benefits to the practice of medicine, including the practice of medical education, the complexity of medicine today demands situation-specific insights to respond to the ever-present reality that standards are enacted by unique individuals in unique contexts. While this can be destabilizing, this study

extends the theory of thresholds of principle and preference (Apramian et al. 2015a) by demonstrating that procedural variations matter. Surgical procedures are embodied, plastic assemblages of sociomaterial actors. We need not fear that designing learning experiences which treat procedural variation as practices which resist standardization will negatively impact surgical education. Quite the opposite—if we try to standardize a competency, it comes at the expense of adaptive capability (Bates et al. 2019; Schuwirth and Ash 2013). If we shift root metaphors for surgical education from standardization to stabilization, we can help residents achieve stable-for-now embodiments of performance which are safe in their hands as their practice thresholds continue to emerge.

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