Exploring the Potential for Touchless Interaction in Image-Guided Interventional Radiology

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ABSTRACT

The growth of image-guided procedures in surgical settings has led to an increased need to interact with digital images under sterile conditions. Traditional touch-based interaction techniques present challenges for managing asepsis in these environments leading to suggestions that new touchless interaction techniques may provide a compelling set of alternatives. In this paper we explore the potential for touchless interaction in image-guided Interventional Radiology (IR) through an ethnographic study. The findings highlight how the distribution of labour and spatial practices of this work are organised with respect to concerns about asepsis and radiation exposure, the physical and cognitive demands of artefact manipulation, patient management, and the construction of "professional vision". We discuss the implications of these key features of the work for touchless interaction technologies within IR and suggest that such issues will be of central importance in considering new input techniques in other medical settings.

Author Keywords

Image use, ethnography, medical practice, touchless interaction, fieldwork, gesture input

ACM Classification Keywords

H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

Since the mid-1970s, advances in medical imaging techniques and instrumentation have allowed new forms of image-guided medical procedures to develop. Such advances have had widespread impact in many clinical areas, the most obvious being a reduction in the number of major surgical procedures carried out. These developments have also led to the growth of new clinical specialist areas, one being the field of Interventional Radiology (IR). In IR, radiologists carry out minimally invasive vascular operations by inserting wires and catheters inside blood vessels using a range of radiological imaging techniques (such as X-ray fluoroscopy, ultrasound, computed tomography and magnetic resonance imaging) to precisely target therapy. These therapies may address problems in the blood vessels themselves (such as the opening of blocked vessels) or may use the vascular system as the method for carrying out other kinds of treatment (such as performing biopsies, or delivering chemotherapy treatment directly to a tumour). Using these techniques, interventional radiologists do not see inside the body directly, but rather are completely reliant upon images for an indirect view. This intensive image-dependency means there is a continuous process of image production and use throughout these procedures for guidance, reference, diagnosis and documentation. As such, there is substantial interaction with technology to capture, browse and manipulate images.

Of further significance is that interaction with images in IR takes place within a surgical as opposed to a purely diagnostic context. This introduces the need to maintain boundaries between sterile and non-sterile features of the work and environment. With traditional interaction techniques for manipulating and browsing images (such as keyboard, mouse or touchscreen), the touch-based nature of input introduces the potential for the boundary between what is sterile and non-sterile to be violated. Avoiding breaches of this boundary is not a simple question of introducing wipeable surfaces or sterile covers for input devices, this being impractical when equipment may need to be used both by sterile and non-sterile team members. Rather, such avoidance is currently managed through the particular ways the work of IR is collaboratively organised across the surgical team and in terms of the spatial arrangement of people, artefacts and instrumentation during the procedures. Several authors, though, have pointed out the restrictions this imposes [12, 22]. For example, Graetzel et al. [12] describe a scene where a surgeon instructing an assistant took 7 minutes to direct the assistant to click on the exact and appropriate place of the interface. While an extreme example, it illustrates the potential communication difficulties associated with image manipulation by proxy, in particular when the proxy does not share the same level of "professional vision" [11].

The need for touch-based interaction has other implications too, beyond issues of asepsis. For example, Wachs et al, [22] discuss the fact that the requirement to interact with touch-based technology means that surgeons are required to

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move away from the patient to where the technology is located to browse or manipulate images.

In response to these limitations, researchers have developed new experimental systems such as Gestix where interaction with images in surgical settings is achieved through gesture recognition techniques based on camera input [12, 21, 22]. At the same time, new technologies such as the "Kinect" system for Xbox gaming signals a new enthusiasm for expanding the ways in which gestural input might be used [20]. Alongside computer vision-based system, other kinds of technical systems also offer new possibilities for touchless interaction such as ultrasound [17].

Our interest too is to explore possibilities for touchless interaction techniques within medical settings. For the reasons outlined above, IR seems, at least *a priori*, a promising context within which to begin looking. However, notwithstanding the plausible rationale underpinning this approach, arguments for developing such prototypes have not, to date, been well articulated within the broader system of work that takes place in these surgical environments. Systems developed from the medical side have remained experimental, and generally have not fully explored the technological possibilities for touchless interaction design. From the technical side, the proposed systems are often based on a simplistic characterisation of the work which belies the complexities of actual practice.

It may be, for example, that methods currently used to work around constraints such as asepsis have additional benefits that might be lost if replaced by a touchless interface. To follow on from the example introduced above, while delegation to a proxy may introduce some communication difficulties, this delegation may also enable sharing of cognitive load inherent in this interaction or provide the operator with someone with whom they can discuss and develop their thoughts [16]. Important then, is how aspects of image production, manipulation and use are collaboratively organised and achieved by the broader surgical team in an integral way with other aspects of surgical procedure. Understanding the details of these practices and *why* they are organised in particular ways is essential to judging when and where it may be appropriate to introduce such technological interventions and essential to inform specific aspects of their design.

With this in mind, in this paper we present an ethnographic study of minimally invasive image-guided procedures within the IR department of a large NHS hospital in the UK. Before moving on to the study, we discuss the related literature to ground our understanding and discussion.

RELATED WORK

Over the years, IR has been the subject of several sociological enquiries. A seminal study by Stephen Barley involved a year-long ethnography in two North American Radiology departments [2]. While the focus of Barley's ethnography is different from our own, his concerns are (like ours) with the relationship between technology and social structure. More specifically, he focused on how changes in the "*interaction order*" [10] brought about by new imaging technologies in radiology departments have created shifting structures and relations. For him, of particular significance is the relationship between radiologists and imaging technicians such as radiographers. Traditionally, the role of the radiographer has focused on the *production* of images rather than their *interpretation*, the latter requiring the specialist knowledge of radiologists. With new technologies and imaging techniques, more interpretive knowledge has become a necessary part of image production. Thus, while sometimes enhancing the role of the radiologist, these changes have threatened to undermine the traditional system of professional dominance within the field. Following this, Burri [4] argues that radiologists needed to renegotiate their visual expertise and reconstitute the professional boundaries between radiologists and radiographers. For our concerns, such boundary work helps understand motivations behind the ways imaging practices are shared across different members of the surgical team.

Additional studies of IR have been conducted by Cramer [6] and Lammer [19]. Cramer focuses on potential uses of Virtual Reality technology within IR, eliciting requirements to this effect. But there is little in the way of thick descriptions of the work to inform our more specific understanding of imaging practices. In contrast, Lammer provides a much richer source of detail about procedures within IR. She articulates the eyes-on, hands-on tactility of the radiologist, whereby tactile resistances from wires and catheters are combined (*"mutually interpenetrated")* with x-ray image "*roadmaps*" to explore inside the body. As we see later, this eyes-on, hands-on combination is significant in how IR work practices are collaboratively organised and how touchless gesture-based actions might be used.

Another important issue here is that a patient in IR is not the *"passive patient-body"* that Hirschauer [16] describes in the case of traditional surgery. In IR, the patient is awake rather than anaesthetized, having implications for the work of the medical team. There is a need to manage the patient during the procedures through talk and a need to manage the nature of talk between team members. This is also highlighted in Hindmarsh and Pilnick's [14, 15] study of anaesthetists where they describe the changes in the behaviour of the team as the patient loses consciousness. Whilst the patient is awake, the team "camouflage" their communication with one another to maintain professional medical performance in front of the patient, such as using gestures to communicate outside the patient's field of view. Once the patient is asleep, the nature of social interaction in the room changes and staff begin to chat among themselves. Again we pick up this theme later in our own fieldwork and our discussion of touchless interaction opportunities.

Our work, too, is informed by more general social studies of work practices in operating theatres [e.g. 5, 8, 9, 16, 18, 23]. In several of these studies, the analysis highlights the performance of the surgeon, their emotional stance, how they maintain *role distance* and the hierarchy of the surgical environment [e.g. 9, 5]. While these help understand aspects of work practice, more central to our concerns are those whose analytic focus is asepsis [e.g. 16, 18] and the social organisation of teamwork [e.g. 14, 16, 23].

Regarding asepsis, the work of Pearl Katz is most notable here [18]. Drawing on arguments by anthropologists such as Mary Douglas [7], Katz focuses on the ritual behaviours within the operating theatre in relation to the boundaries between different "*realms of cleanliness*" – sterile and contaminated – and involve constraints in terms of movement and the spatial organisation of work. After all, scrubbing up is time consuming and effortful and therefore not engaged in without good reason. Important in managing these boundaries is an organised distribution of labour between scrubbed and non-scrubbed personnel (e.g. in providing a sterile needle, a non-scrubbed assistant opens the non-sterile outer packaging, not touching what is inside, and reveals the sterile needle to a scrubbed assistant, who touches only the sterile needle and not the packaging). In IR, there is a need to extend Katz's arguments to consider another kind of "contaminant", namely contamination through radiation from x-ray imaging. As with notions of asepsis, we see that the ritual work of IR is also organized to minimize the risk of prolonged exposure to radiation, affecting spatial zones, barriers, timing and the division of labour. This is a theme we pick up later in the findings.

The issue of teamwork in the operating theatre is further explored by Hirschauer [16] characterising the surgical team as the *"surgeon-body"*. This concept is used to highlight how team work is achieved through a "division of labour and hierarchic organisation", functionally extending the surgeon with complementary "additional 'right' and 'left' hands'", through, for example, nurses passing him instruments, the co-ordination of the surgeon-body through words and gestures, and the anticipation of actions by the skilled team without the need for explicit requests by the surgeon. Professional anticipation is also discussed in Hindmarsh and Pilnick's study, detailing how team members recognise the *"trajectory of action"* to make inferences about the anaesthetist's future actions and intentions based on their current actions [14, 15]. Hindmarsh and Pilnick argue that for this recognition, anticipation and coordination to occur, the embodied and "tacit order of teamwork" in these settings is crucial. By highlighting the interaction details of this work, they articulate how the gestures, talk and action of teamwork are not only understood, but how they are produced and made visible in relation to the spatial and material arrangement of people, objects and artefacts.

This embodied account of work practices leads us to a final area of literature useful for grounding our research and concerns the reading and interpretation of images. While there are many studies of image reading in scientific and medical contexts, there are some common concerns that we want to illustrate through discussion of some examples. Of particular significance is Goodwin's notion of *"professional vision"* [11]. For Goodwin, professional vision comprises the "socially organized ways of seeing and understanding events that are answerable to the distinctive interests of a particular social group". This vision is built through the production and manipulation of material representations - for example, medical images. Drawing on Goodwin's work, Hartswood et al [13] argue that particular professional groups adopt a repertoire of representational manipulations and techniques to make professionally relevant things visible and interpretable. With a particular focus on diagnostic radiology, these include, for example, the particular way a magnifying glass is positioned against a mammogram or the annotations used to mark up representations. Important here is that this reading of images is a dynamic, embodied and interactionally-organised process. This is further illustrated in Alac's work on analysis of functional Magnetic Resonance Imaging (fMRI) images which highlights several issues [1]. First is how the rapid alteration of images is used to create a kind of motion where differences in the images are perceived and understood as a dynamic whole. Second is the close coupling of gestures to images on screen. These gestures are imagined transformations of the image. For example, they may make squashing or shearing actions in front of the scan image, or they might mime rotation of an imagined 3D version of the brain above the 2D fMRI image. These gestures are not simply making direct reference to static objects on the screen, however. Their meaning is bound up with the accompanying talk. This use of environmentally coupled gestures in interpreting images is important for how machine-readable gestures might be introduced into medical settings without interfering with this embodied act of seeing. As Barre et al [2] argue, gestures or "movements that have a meaning" are a subjective concept –meaning depends on a person or machine's perspective.

Drawing on insights from the literature, we present findings from a study of image-guided IR. The focus of our analysis is the collaborative production and use of radiological images in the context of IR procedures. Following the analytic orientation of authors such as [15], our findings articulate interaction details of how gestures, talk and action are produced, coordinated, made visible and understood in relation to the spatial and material arrangement of team members, objects and artefacts. Further, we articulate how this work is shaped and constrained by issues of asepsis and radiation exposure. Using this understanding, we discuss implications for how touchless gesture-based image manipulation might be used in such environments.

IR IN THE ANGIOGRAPHY SUITE

Our fieldwork focuses on work practices and interactions in the angiography suite of a large UK hospital, the suite shown in Figures 1 and 2 (plan and photo respectively). The x-ray table is positioned underneath the x-ray image intensifier, providing the focal point for the room and around which various pieces of medical equipment and furniture are positioned: the instrument trolley, x-ray control foot pedal, mobile x-ray control unit, contrast medium injection pump, ultrasound machine and mobile radiation protection screen. At the room edges are scrub sinks, work side and shelves full of wires, catheters and other procedural paraphernalia. Above the x-ray table is a bank of four monitors (three in one row, the fourth above the middle one of the 3 screens) mounted on a single lever arm allowing the monitors to be positioned anywhere above the x-ray table. The left-most screen will show live fluoroscopy images; the middle screen, reference images from angiographic runs; the right-most screen will remain mainly blank but can display other useful images (e.g. from previous procedures or other imaging modalities) if required. The top screen shows the position and angle of the x-ray scanner. In the lower left corner of the room is a bank of computers (on a bench behind another radiation protection screen) used to control and manipulate images presented on the monitor bank above the patient. The door in the lower left corner leads to two further rooms where administrative procedures, form-filling and discussion relating to the operations take place.

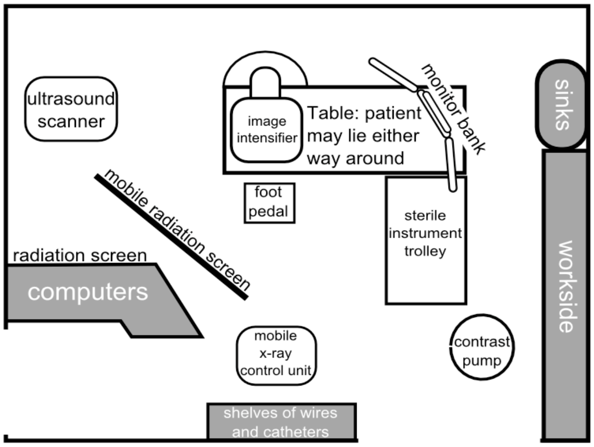

Figure 1: Approximate layout of the operating room. Solid items are mobile and rearranged to suit each procedure.

In our fieldwork, we observed six IR procedures over two days, several weeks apart. The procedures were typical and routine practice, mainly involved the insertion of balloon catheters into blocked or narrowed arteries, the balloons being inflated to widen the affected areas. Some also involved the insertion or removal of umbrella filters designed to capture blood clots. These observations provided a contextual understanding of the settings and real time coordination of action. During the observations, we were based in the area behind the fixed radiation protection screen. This is only a partial screen both in height and in length but demarcates a radiation-safe zone. It is open to the rest of the room allowing visible access to the whole room and good aural awareness of ongoing talk. During the observations, we could informally interact with the staff (radiologists, radiographers and operating assistants) providing an opportunity to discuss and explain procedures as they were happening. This allowed us to elicit detailed explanations of the pathologies and procedures being undertaken, details of interactions with particular equipment, interpretations of images, and explanations of talk and actions. In two of the procedures where only one radiologist performed the intervention, the second radiologist provided us an ongoing commentary that explained the actions and material arrangements being observed during the procedure. At breaks before or during the procedures we undertook longer in-depth interviews with team members to further clarify our interpretation and the reasons for particular behaviours.

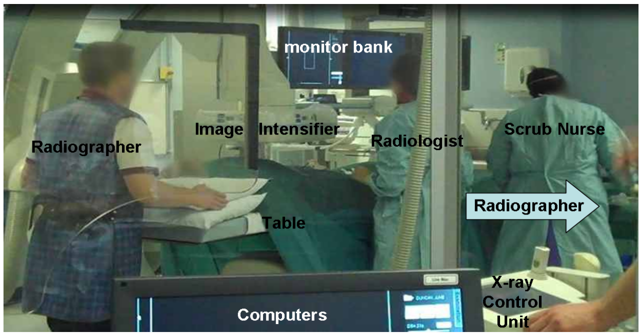

Figure 2: View towards x-ray table from computer area.

In addition to field notes, we collected audio and video recordings of the procedures and interviews. Within the contextual understanding of the *in situ* observations, the recordings enabled a more detailed, reflective and systematic analysis of the unfolding action than was possible during in-the-moment observations. By conducting video analysis of the first session, issues were raised that were further explored on the second observational visit.

FINDINGS

Following a brief scene setting, the findings are organised around three key stages common to all of the procedures we observed. First, we discuss the creation of the angiographic run. We then articulate the work practices comprising review of the angiographic run and selection of appropriate reference images. Finally, we describe the use of the reference image to guide subsequent treatment.

Prior to the procedure, the team engages in preparation of themselves, patient and equipment. Two operating radiologists (medically trained doctors and specialists in IR) are present to conduct the procedures. Most of the time, both will conduct the procedure together, but for less complex cases, only one will be actively involved, the second serving mainly as backup and for discussion. The radiologists scrub up before donning their sterile gloves and gown. For protection from radiation exposure, they put on lead aprons, lead collars and protective glasses. The radiologists are supported in the procedure by a scrub nurse (also in sterile gown and gloves) as well as a number of circulating nurses (non-sterile). Also in support are one or two radiographers (at least one is specialised in angio-radiography) who prepare and help operate the x-ray equipment. The radiographers are not sterile but do wear lead aprons. A scrubbed nurse cleans the patient's skin and places a sterile drape over the patient's body. Various protective polythene covers are placed over the equipment (e.g. foot pedal, image intensifier, mobile radiation protection screen) as infection control measures.

Creating an Angiographic Run

Once the patient is prepared and the artery accessed, the procedure turns towards the creation of the first "angiographic run", a set of high-resolution x-ray images that allow the radiologists to see the arteries, assess blood flow and detect any blockages. To create these images, a radiologist first inserts a needle and guide wire into the patient's artery. In all but one of the operations observed, the wire was inserted at the groin (in the other they entered a vein in the neck). Once the wire end is in the artery, they begin fluoroscopy, an imaging technique that provides a continuous series of x-ray images at a frame rate of between 10 and 30fps. The positioning of the x-ray machine is remotely controlled by the radiographer standing away from the table using a mobile unit under instruction from the radiologist. A foot pedal controlled by the radiologist is used to trigger image capture, which is then displayed on the left most screen in the screen bank. Fluoroscopic imaging is both low dose (with dosage being reduced as frame rates drop) and low resolution, and at 10 frames per second shows movement of the wire as it is twisted, manipulated and guided down the artery.

One of the limitations of fluoroscopy, though, is that it shows the bones and wire but not the blood vessels themselves (see Figure 5 (right)). To see these, the radiologists inject a contrast medium (often called dye when discussing with patients) into the artery that will show up on the x-ray. This is done by putting a catheter along the route of the guide wire. One of the radiologists then injects the contrast medium into the catheter either by hand or using a pump depending upon the rate and length of flow required. As the contrast flows through the arteries, the radiologist, again using the foot pedal, triggers a series of high resolution, high radiation x-ray images. Generally these are taken at low frequency (two per second for up to forty seconds) constituting an angiographic "run". Concerns over radiation exposure can already be seen in the high level organisation of this process. Key here is how the procedure combines low-dose (high frequency) fluoroscopy with high-dose (low frequency) angiographic runs where there is a trade-off between number and quality of the images and the amount of radiation exposure. Important too are levels of radiation exposure over time, especially for radiologists constantly working with this technology. Any way exposure can be avoided or reduced has significant consequences in the longer term. Runs are executed only when really needed, to limit exposure.

Positioning the scanner

To show the correct part of the patient, the position of the x-ray machine needs adjusting. In theory, a single radiologist can adjust this at the x-ray table; in practice, this control is shared. Consider this interaction between radiologist (R1), radiographer (Rg1), and the patient (P):

R1: North please… thank you stop there. Wire out, I'll have a J wire back please, thank you. Open sides a little bit for me now please. And up down a bit more. Thank you, keep going up down. Thank you… Fine, wire out thank you. P you're going to get a bit of that warm feeling from that x-ray dye I told you about. OK, if you feel like you're going to wee don't worry.

P: I felt like it earlier on.

R1: Did you? Well haven't put any in yet, but I'm going to now. So… Yep, did you get that? OK it will be a bit more intense when we get the proper pictures alright? OK.

P: It feels as though it's molten actually.

R1: Yes it will. Absolutely, it will do a little bit. That's great, OK let's get set up for the peri run now then. Better bring the table vertically up M [Rg1]. Do you want to go vertically up then I can get the table up a bit higher. That's good we can keep it this way round cos then we can get that all on. OK M [Rg1] that's fine. Just got to get some preliminary set up pictures sorted now P. Those'll be ready to go. Err sorry, hang on hang on. Just go back up, the left side is the one we're more interested in, and it mustn't come across. That's good, sorry. Yeah Ok?

Rg1: Sorry, I took your…

R1: I know I take my foot off. Can we get the legs a bit closer together? P, we just need to try and get your knees a bit closer if we can.

At the beginning of the snippet, we see an example of instructions used for positioning the image intensifier and tube c-arm of the x-ray equipment. "North" indicates movement towards the patient's head; "south", towards the patient's feet. The radiologists also specify things such as size of area being scanned to adjust the amount of detail or context shown or to create more room under the intensifier for the radiologist to work , e.g. "Open sides a bit". Further instructions refer to the type of image they want, frame rate of the images and whether a filter should be used. These parameters are dependent upon the procedure and factors such as the size of the patient for example. Sometimes, these instructions might be very specific and precise in their description. Often though, as we see above, there is a continual negotiation between radiologist's instruction and radiographer's action, until the desired position is reached. At this point, the precision of adjustment is difficult to achieve through instruction requiring the radiologist to assume control. The radiologist uses a button on the side of the x-ray table to complete the positioning through fine level adjustments of table height and position.

To further understand this distribution of labour across radiologist and radiographer we need to consider some other factors. At these times, the radiologists typically have their hands full holding and manipulating the wires and catheters. The radiologist uses the foot pedal to initiate the fluoroscopic imaging (displayed on the left hand screen). During this time, their eyes are fixed firmly on the left-hand screen watching the wire or catheter move. While watching, they combine what they see on-screen with what they feel in their hands. As one radiologist describes it:

"You have to learn to not necessarily look at your hands… Hands work almost automatically but all the action's with the eyes on the screen…. if you're feeding the wire in and it's running nice and smoothly that's OK. The minute it either stops or you get a bit of resistance the thing not to do is just push like fury because you can damage the artery. You have to stop and either take it out and get a bit of dye or pull it back and twiddle or what have you."

Viewing images is combined with a sense of touch to "see" what is going on inside the body. This is cognitively *and* physically demanding. Indeed, sometimes both radiologists are needed to hold wires in position or one holds while the other injects contrast. Thus, support from radiographers in positioning the intensifier and setting up the image is key, but only where articulation and mutual understanding of the parameters can be successfully and efficiently achieved.

Timing the scan

Crucial issues of timing also affect the organisation of this work as indicated by the radiologists' use of the foot pedal. Use of the foot pedal is evidence that the hands of the radiologists are full but also an indicator of the radiologist's need for control rather than delegating to the radiographer. Timing the trigger is delicate, needing close coordination with wire and catheter movement, contrast injection and movement of the radiologist's hands away from the primary x-ray beam to avoid exposure.

R2: We need to activate the x-rays because of your fingers being so close. You have two hands on something; the sensible thing is your foot.

Int: Why can't these guys [radiographers] activate the x-rays?

Rg2: Because we don't know where their fingers are.

R2: Because my fingers might be in the primary beam. I might be fiddling something and if they press 'go' your fingers would get it all the time.

The intricate nature of screening in these procedures means the timing of these manoeuvres is particularly fine-grained, Achieving synchronised movement with the radiographer is difficult and not conducive to control through coordinated instruction and distributed labour. It is also significant that the foot pedal is mobile. The radiologist will move the foot pedal to allow triggering of the imaging as far from the x-ray machine as practically possible depending on the manoeuvre and whether they need to be holding or manipulating something, such as injecting contrast medium by hand or pump. This positioning is constructed in an effort to minimize radiation exposure.

Managing the patient

A further factor affecting the shared organisation of work in these procedures is patient management. During IR procedures, the patient remains awake. As we saw in the first snippet, coordinating talk between team members is interleaved with utterances for patient management – explaining what is happening, what they will feel etc. This is in part about patient reassurance but is also important in image production. For example, if the patient moves during a scan, this inhibits production of a clear image. Informing the patient of what they should expect to feel better enables the patient to control involuntary movements in response to these feelings. They will also be instructed to hold their breath, keep still or position body parts in certain ways while the angiographic run is taken. So again we see here aspects of image production work that are mentally demanding for the radiologist as well as aspects requiring closely-timed coordination of triggering with the instructions to the patient. The mental demands and critical timing of instructions affect how image production is managed across radiologist and radiographer.

Summary

What we see so far are the ways some actions are delegated across the team, and others are taken literally "in hand" by the radiologist. The work is mentally and physically demanding, so delegation happens where possible. At the same time, the radiologist needs control when fine adjustment or closely-timed coordination is needed. Any input mechanism for this phase of the work thus needs to support these kinds of actions, bearing in mind that the eyes and hands may be fully engaged elsewhere.

Reviewing the Angiographic Run

As a run is created, the radiologists watch the left-hand screen above the patient, viewing images in the run as they appear. While not a detailed inspection, this initial observation allows judgment of the run quality (e.g. whether the images are clear or blurred). Once satisfied, they need to review the run and create a *"reference image"*. It is at this point that we see an important transition in the organisation of the work. The radiologists move to the area behind the radiation screen to view and manipulate the images at the computer terminals there. This involves them entering and working in a non-sterile zone, a significant transition because the traditional ways of maintaining sterile and non-sterile boundaries no longer apply, namely, the spatial organisation of work, and the division of labour across scrubbed and non-scrubbed team members in different zones. Understanding why this happens is therefore important to our concerns.

Ideally, movement from sterile to non-sterile zones and back again would involve de-gloving in order to handle non-sterile equipment and then re-scrubbing and gloving to return to the sterile area. Such behaviour is time-consuming and, given this is done several times during a single procedure, could potentially add significant time. These time concerns are not simply about organisational efficiencies and cost, but also patient safety. Adding time to a procedure brings additional risks and potential complications to the patient (e.g. greater risk of blood clotting). Given these time constraints and a need to interact with the images using the non-sterile mouse, they make a judgment that balances these concerns. This balance involves a creative workaround that maintains strict boundaries between sterile and non-sterile as embodied in different parts of the radiologist's gown [cf. 18]. The outer front part of the gown is sterile, the inside, non-sterile. The cloth of the gown, then, *is* the boundary between these two conditions. With their sterile gloved hands, the radiologist grabs the sterile front of the gown, carefully hoisting it up and flipping it over their gloved hands. As seen in Figure 3, the non-sterile part of the gown is used to touch the mouse to manipulate and inspect the images. The infection control nurses we spoke with expressed concern about these workarounds, however they conceded it was the best available solution given that the radiologists needed to directly control the computer during the procedure.

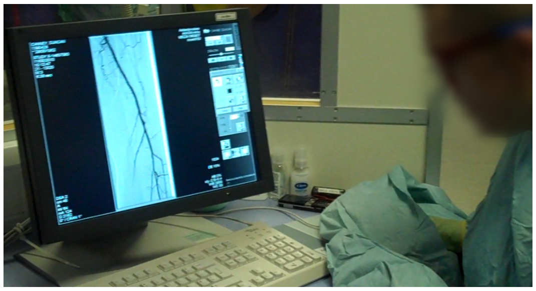

Figure 3: Radiologist using the mouse through his gown.

This raises the question of why radiologists adopt this work-around to directly control images in the non-sterile area. What are the radiologists doing that cannot be delegated to the radiographer who, after all, is both non-sterile, and a competent user of the software? The answers are found in a closer look at what the radiologist is achieving. First the radiologist moves sequentially through the images in the run. Using the mouse, they click on the right or left side of the image to move forward and backwards through the sequence respectively. As they browse the images, they click very quickly until they reach the image segment of interest. At this point, they step through the images more slowly, moving forward and back as they inspect particular features on a single image as well as the nature of blood flow shown by the sequencing of images. The temporal sequencing of images shows progression of contrast flow through the arteries providing important indications of pathology, e.g. if a large section of artery doesn't fill up or blood flows into minor branching arteries, this indicates areas of blockages or narrowing. Moving through the images corresponds to moving through time. Interpreting this flow relies not just on a visual sense but also on a feel of the pacing through the images. Directly controlling speed and direction of image sequencing enhances the radiologist's ability to interpret the images:

R1 "It's when you actually sit down and you want to look in more detail, and sometimes you're watching the blood flow say, coming down one artery and you want to see what happens, so you want to go forward a couple, it's almost like on the television or video when you're rewinding and go forward – so we want to come back and think it's coming there, there and then where's it going there etc. So that's just then we just want more control, and something about your own finger controlling the rate at which the image moves as you're looking at a certain area."

This review of the images is done side by side with the other radiologist. While looking at the images, they gesture over and point to particular features (see Figure 4), collaboratively interpreting the images and discuss the next steps in the intervention. This gesturing makes deictic reference to particular parts of the image as well as acting out more dynamic actions relating to current flow, suggested interventions and flow consequences of these interventions [cf 1]. As they inspect, they lean into the screen to see finer detail. These activities are the radiologists' *"socially organized ways of seeing and understanding"* [11]. Their professional vision is actively and collaboratively constructed through these activities and depends upon their specialized knowledge of the pathology.

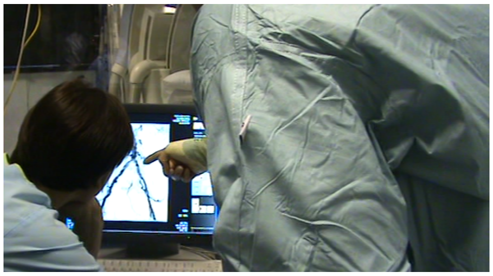

Figure 4: Radiologists gesturing over the angiographic runs.

Manipulating the mask

During this stage, the radiologists also need to manipulate the images in other ways. These manipulations are again for creating good quality reference images but also support active diagnostic interpretation of the 'run'. The manipulations concern the image mask used for the purposes of *digital subtraction* (see Figure 5). Before a run is taken, a base x-ray of that part of the body is taken. This image, the mask, contains all the bones and tissue that will appear in the background of the run. To see the arteries in the run more clearly, the mask image is subtracted from the run images removing the bones from the background and revealing the contrast filled arteries in the foreground. This is automatically done to the run before it appears on screen (though bones can be revealed again by clicking a button).

While the images in the run are taken, a patient may move causing the mask image to be misaligned. This means outlines of the bones and other objects will appear. These outlines are problematic as they might be mistaken for arteries or obscure key parts of an artery. This can be corrected by realigning the mask image automatically or manually. The automatic realignment finds a global best fit for the mask but takes roughly a minute for the algorithm to execute. The manual option allows the radiologist to move a selected section of the mask so that it covers an area of bone better. Often, radiologists prefer manual adjustment for speed and ability to select specific parts of the image for correction. To make this selection, the radiologist uses the mouse to draw a selection box over the area and then "drags" this box to move this area of the mask until the bones disappear or the arteries are clearly visible. This movement of the mask is fine-grained with movements less than one millimetre onscreen often a sufficient adjustment. Again, while radiographers know how to do this in terms of controlling software, the radiologists like to do it to see how manipulating the mask affects specific areas of the image. In addition, because of the fine granularity of selection and movement, articulating the selection precisely is non-trivial and dependent on the *professional vision* of the radiologist.

R1: *"Again we can say "oh I want to see such and such an artery", but sometimes you just want to see a tiny bit of an artery and that's when we like to get hold of the mouse… Because what we see and what they see… obviously the radiographers are not specifically doing it to look for the pathology – we're looking for the pathology…Undoubtedly sometimes when we actually sit down there and go through the imaging again, particularly in some of the longer more difficult cases, you go through it you may actually spot something that you didn't see at all at the time."*

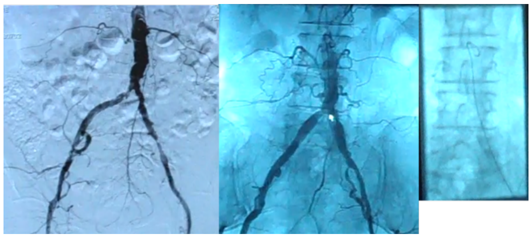

Figure 5: (Left) digitally subtracted image from an angiographic run. (Centre) image from angiographic run with bones. (Right) 'real time' fluoroscopy image.

Retreat and reflection

In theory, this interpretation and manipulation of the images could take place at the x-ray table since the monitors there 'mirror' the computer terminals behind the radiation screen. However, moving behind the radiation screen was an opportunity to retreat from the patient and reflect.

R1: "Sometimes it is just quite good (a) to be away from the patient and the other thing is somehow sitting down, you're sort of leaning forward a bit staring at the screen, actually having your backside parked and moving the images to-and-fro, rather than thinking on your feet. Sometimes it may not have ended up as you might have liked initially. It's quite nice to move away and think oh bother what am I going to do now rather than standing there chuntering on about it. It's quite nice to have a retreat. You don't have that in the operating theatre, when they're asleep."

With the patient conscious throughout, withdrawal to the non-sterile area provides valuable opportunity to openly discuss problems and uncertainties away from the patient. This is similar to observed transitions from "camouflaged" to "non-camouflaged" talk among anesthetists as patients move from conscious to anaesthetised state [14].

Summary

In this phase of the work, again we see the radiologists' need to be "hands-on" to navigate through and manipulate images to gain deep understanding of the situation for diagnosis and planning. Often this is done in consultation with another radiologist. Features of this include quick navigation, detailed manipulation, close facial proximity to the screen, and interleaving of communicative gestures with system input. Here, an important feature of the mouse as input is a clear demarcation between communication with the system vs. communication with people via speech and gestures. Touchless interaction would need to attend to these features, allowing seamless collaboration coupled with fine-grained, efficient control. This analysis also suggests a need for interaction away from the patient in a place where radiologists can talk and reflect.

Using the Reference Image

Having reviewed the images and planned the treatment, the radiologists choose an image as a reference *'roadmap'* showing the network of blood-vessels along which the radiologists have planned a route. Using the computer behind the radiation screen, this image is displayed on the lower middle screen above the patient. The radiologists return to the patient to proceed with corrective intervention. In many ways, this stage is similar to that of the initial angiographic run in its use of fluoroscopy image guidance. The key difference at this stage is the level of precision and intricacy involved in positioning of the catheter. For example, balloon catheters need to be positioned precisely where the narrowing of an artery occurs, and inflated to the correct size to widen the artery appropriately. A fluoroscopy image only shows certain features to guide this positioning: bones, the wire, markers at the top and bottom of the balloon, and other clues such as calcification landmarks. The arteries are only visible on the more detailed static reference image from the angiographic run.

R1: "If the wire comes down there… and we've got a reference image with that artery on it we can work out the distance from the bone – your eyes always work from a reference point and often we use the femur as our reference point. So your eyes then work out how far in from the femur you are… because we know particularly there's another artery that comes over here somewhere there, so if we see our guide wire coming over here much closer to the bone then we think 'ahh we're in the wrong artery'… you're usually scanning to and fro to work out roughly are we going in the right direction."

As discussed earlier, the radiologists' eyes are on the screen as they feel their way with wires and catheters. Here, though, there is constant to-ing and fro-ing between the live fluoroscopy image and reference image comparing distance from bones or shape of the wire in relation to the arteries.

The work in this phase is again highly collaborative, sharing many features with the initial creation of the angiographic run. Rather than reiterate these, of significance here is further collaboration between radiologists and radiographers in relation to image referencing. Here we see, in common with studies of anaesthetists [14, 15] and surgeons [16], the anticipatory actions of teamwork. For example, a radiographer will anticipate a radiologist's need to inspect images by interpreting the body movements and gaze of the radiologist in relation to the orientation of the patient. They move the monitors to allow more comfortable and closer inspection of the fluoroscopic and reference images together.

Also of note is the dynamic nature of this "roadmapping" work and its collaborative achievement. At different points in the procedure, reference images of different body areas may be needed. Furthermore, for a particular reference image, certain features need to be dynamically revealed or removed to highlight features otherwise obscured. When this occurs, the selection and display of different images is negotiated between radiologist and radiographer. From the display behind the radiation screen, the radiographer, under instruction from the radiologist, will find a different run– the display being mirrored on the monitor above the patient. The radiologist views the display above the patient as the radiographer flicks through the run. While the radiographer knows broadly which part of the run the radiologist wants, the radiologist needs to make the final selection, watching as the radiographer clicks back and forth through a set of images. Once the image is selected, the radiologist requests the mask image be removed to reveal the bones (providing the necessary landmarks), providing a new roadmap for display on the screen bank above the table. While this selection requires a level of professional vision, hands-on control by the radiologist is not as critical as in the previous stage. Much of the analytic work on the images has already been done by the radiologist, making navigation and articulation of the correct image simpler. Thus, the task can be shared by radiologist and radiographer, enabling spatial boundaries of sterility to be maintained.

Finally, having treated the arteries, the radiologists take another set of angiographic runs and return behind the radiation screen to review the images (in the same way as outlined earlier). At this point, they may decide the treatment has been successful or return to the table for further intervention, going through the key stages outlined.

Summary

The importance of the reference image has been highlighted showing that, while sometimes the radiologist selects and creates it, at other times this is done with assistance from the radiographer. The need for ad hoc access to new reference images while at the x-ray table points to where touchless interaction might provide more flexibility for the radiologist to take control at certain points in the process, without necessarily taking the radiographer out of the loop.

IMPLICATIONS FOR TOUCHLESS INTERACTION

Through the fieldwork, we have articulated the work practices of an IR team with a particular focus on how images are collaboratively produced and used within the context of the surgery. Critical in the organisation of these practices is an orientation to boundaries between what is sterile and non-sterile and levels of radiation exposure. We have seen too how the mental and physical demands associated with instrument manipulation, attending to a screen and issues of patient management also play a central role. All of these factors impact how work is distributed across different team members, its spatial organisation, when control needs to be maintained by radiologists, when it can be delegated, and detailed timings of coordination.

In light of the findings, we return to our initial motivations for the study, namely, a critical assessment of the potential for touchless interaction technology in these settings and particular design considerations. One key set of findings concerns the importance of the radiologist sometimes being in control of navigation and manipulation of data. For reasons we have outlined, this is sufficiently critical that radiologists find work-arounds to achieve this. This raises the question of whether touchless interaction could make this easier, and whether there are other points where this approach would allow more flexibility for interacting with data. In other words, can these new input techniques allow their being "hands on" without literally being hands on?

One area of significant opportunity is for image-based interactions behind the radiation screen. We saw important reasons why radiologists retreated behind the radiation screen to allow reflective interpretation and private discussion of the images. Further, the radiologists need direct control over the images here, being integral to their analytic interpretation. Touchless gesture-based interaction for image browsing and manipulation at these points would maintain the boundaries between sterile and non-sterile avoiding the need to interact through the gown. However, deploying a touchless access point here raises a number of design considerations. The first concerns the communicative gestures and deictic references to the images employed by the radiologists during this work. A touchless system needs to distinguish these communicative gestures from those intended for interaction with the system. There are different ways we might approach this. For example, one way would be to designate only certain zones around the screen as sensitive to interaction (such as off to the side of the screen). Another option is to design the system gesture vocabulary to be distinctive from communicative gestures in terms of their spatial property and form. We might also consider particular gestures that delimit the beginning and end of a system engagement. While this solution may inhibit fluid transition between the two forms of gestures, this can be mitigated using bimanual input in which the less dominant hand signals system engagement, while the dominant hand performs the interactive gestures. For any of these solutions, feedback (visual or auditory) will be necessary to indicate when the system is or is not engaged in gesture recognition.

A second consideration here is granularity of control. When interacting with images, radiologists combine simple image browsing with precise selection tasks. Image browsing can be controlled well with relatively coarse-grained gestures; selection tasks require much finer spatial granularity of hand and finger tracking. Touchless interaction technology here needs to support both course and fine-grained tracking through careful design of the gestural vocabulary and how it is mapped to control elements in the interface.

The next area of opportunity for touchless control is around the monitors above the x-ray table. Primarily, this would give the radiologist more flexible control over the selection and positioning of relevant roadmap images to appear on the screens. It could also enable the radiologist to make finer-grained deictic references from a distance to detailed parts of the image benefitting communication with others. Realising such opportunities is not without complexities and requires some qualification. The first issue here concerns the cognitive demands and physical constraints the radiologist is under at these points (e.g. manipulating the catheters). This means that any image selection work is still likely to involve the radiographer under instruction from the radiologist. Issuing high-level instructions is still the sensible way to get to the approximate point in the right angiographic run. But touchless interaction could allow the radiologist to assume responsibility over the detailed selection of reference image, avoiding the to-ing and fro-ing that occurs when trying to specify the exact image. The system design should enable shared control by radiographer *and* radiologist enabling fluid coordination between them.

A second issue concerns spatial location. As we have shown, radiologists need flexibility in terms of their positioning in theatre. Touchless interaction should enable control from different positions and distances from the screen. Thus, absolute position tracking in relation to the screen may not be appropriate. Rather, tracking of movement *relative* to the radiologist's body might be more suitable. A related point is that the system should accommodate input from multiple team members standing in different locations. This also raises the issue of whether simultaneous collaborative control should be possible.

CONCLUSION

In sum, our aim has been to understand the collaborative work practices in IR procedures in terms of image production and use. An understanding of these practices can be used to inform a wide range of technological interventions, but our particular focus in this paper, has been a critical assessment of opportunities and design implications for touchless interaction within these settings. Some of these characteristics are without doubt unique to IR, but by raising issues of control and delegation, system engagement, granularity of interaction, physical constraints, spatial flexibility, and collaborative access, we hope these findings can be used more broadly to think about touchless interaction in other medical contexts too.

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