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# Haptic Simulation in Cerebral Angiography: Establishing New Clinical Competency Targets

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# Abstract

As medical education and specialty training continues to move in the direction of competency-based training, assisted with the progression of simulation-based modules, the importance of establishing objective assessment parameters and performance metrics is becoming more clear. Currently, interventionalist training focusing on endovascular skills in cerebral angiography (an imaging procedure used to diagnose and treat stroke and vascular disorders), continues to rely on quantity of clinical experience rather than its quality, and has lagged in developing objective performance markers. Immersive, realistic, and haptically-accurate simulators have been developed in this field for the purposes of training future expert interventionalists, however, their utility has been washed out due to a poor understanding of transferrable clinical skills and performance markers to be used in medical fellowship programs.

This dissertation assessed the perceived competencies and operational obstacles observed by neurointerventionalists to inform an assessment of diagnostic and interventional skills which can be developed in simulation-based training. Inquiry into clinically significant steps in cerebral angiography revealed a relationship between clinical procedural tasks which were rated to be highly important and risky, such as those associated with vascular navigation and aneurysm coiling. The results of our studies suggest that navigational skills in simulation-based diagnostic angiography training could be improved with independent practice. Furthermore, navigational competency was strongly linked to mental rotation ability, the lack of which could be supplemented with visual assistance overlay tools. Most importantly, the data suggests that independent training of neurointerventional skills, such as aneurysm coiling, in simulation-based training may be an effective method of complementary training with minimal resources, as improvement in aneurysm coiling quality and pace was observed in simulation.

Using objective assessments of targeted skillsets in simulation-based training can alleviate the training burden in neurointerventional radiology and provide performance metrics to improve training standards while minimizing resource waste, including both attending clinician resources and operating room use for training.

# Summary for Lay Audience

Brain aneurysms are a common condition that affects people of all ages and often go undetected until medical intervention is needed. In Canada, approximately 3.2% of the population, or 1.1 million people, live with unruptured brain aneurysms. These aneurysms are often discovered during MRI scans, which occur in almost 2% of all cases. As a result, there is a large population of patients with aneurysms who require medical diagnosis and intervention.

The standard treatment for brain aneurysms is angiography, which uses minimally invasive catheters to navigate the body's blood vessels and locate and treat areas of weakness. These procedures allow patients to be treated and released the same day, but they require interventional specialists with extensive training in order to perform them safely and effectively. Neurointerventionalists can access the blood vessels through the patient's leg, but they must be able to spatially navigate through the lumen, use x-ray imaging to understand their catheter position within the body, and pack an aneurysm in the brain with electrolytic coils carefully controlled at the access site around the patient's thigh.

This complex array of skills is currently only formally learned through operating room-based fellowship programs, which result in high healthcare costs and inefficient skill development opportunities for novice fellows. This thesis has focused on measuring our ability to use simulation in cerebral angiography training by assessing the factors that affect performance and the parts of the procedure best trained using simulation. The research has suggested that moving tools through the arteries and treating the aneurysm are some of the most important steps, and practicing them in simulation on their own helps novices improve and avoid making mistakes critical mistakes. These promising results clarify the skills we need to target to accelerate the inclusion of simulation in training in this field.

# Co-Authorship Statement

The content of this thesis comprises a combination of published and submitted manuscripts (Chapters 5-8). Oleksiy Zaika (OZ) is the first author on all included manuscripts. He was responsible for study design, data collection, interpretation of results, and drafting of the manuscripts.

Chapter 5 was co-authored by Dr. Mel Boulton (MB), Dr. Roy Eagleson (RE), and Dr. Sandrine de Ribaupierre (SR).

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Chapter 8 was co-authored by Dr. Mel Boulton (MB), Dr. Roy Eagleson (RE), and Dr. Sandrine de Ribaupierre (SR).

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# List of Acronyms

| | |
|---|---|
| IA | Intracranial Aneurysm |
| CBME | Competency-Based Medical Education |
| SBME | Simulation-Based medical education |
| ACoA | Anterior Communicating Artery |
| ACA | Anterior Cerebral Artery |
| MCA | Middle Cerebral Artery |
| PCoA | Posterior Communicating Artery |
| ICA | Internal Carotid Artery |
| SUB | Subclavian Artery |
| CT | Computerized Tomography |
| MR | Magnetic Resonance |
| R-VERT | Right Vertebral Artery |
| R-ECA | Right External Carotid Artery |
| L-CCA | Left Common Carotid Artery |
| L-SUB | Left Subclavian Artery |
| R-SUB | Right Subclavian Artery |
| L-ICA | Left Internal Carotid Artery |
| R-ICA | Right Internal Carotid Artery |
| MRT | Mental Rotation Test |
| CON | Control Group |
| INT | Intervention Group |

# Introduction

The fields of neuroradiology and neurosurgery have evolved significantly over the years, with advances in medical imaging technology and surgical techniques leading to the development of new diagnostic and therapeutic approaches. As a result, their shared duties under the neurointerventionalist specialty demand highly skilled individuals to effectively employ imaging modalities and surgical instruments to diagnose and treat a wide range of neurovascular disorders. This requires not only a thorough understanding of neuroanatomy, but also a high level of technical proficiency.

Once a neuroradiologist or neurosurgeon has a strong foundation in the basic principles of their respective specialty, they can begin to develop their technical skills through hands-on training and practice. This typically involves working closely with attendings to develop proficiency in the use of imaging techniques, diagnostic tools, and interventional procedures. The rigorous training protocol is extensive, exhaustive, expensive and primarily experiential. As a result, there is a growing need for innovative simulation-based training programs that can efficiently and effectively teach these technical skills to the next generation of neuroradiologists and neurosurgeons. But how can we ensure that these training programs are effective in preparing the next generation of practitioners for the challenges they will face in the operating room?

In this dissertation, we present compelling evidence for the implementation of structured simulation-based training in interventional radiology fellowships to facilitate novice fellow skill development independent of their attending interventionalist as a complement to their guided apprenticeship in the Angio Suite.

The first chapter covers the fundamental understanding of neurovasculature, aneurysms and diagnostic techniques necessary to understanding the works conducted. The second chapter covers the training that fellows in neurointerventional programs have to undergo and the competencies they have to demonstrate. The third chapter covers the current state of simulation, its benefits and limitations, and its use in endovascular specialties like interventional radiology. The fourth chapter covers the state of integrating the tools available and the questions posed for this research. Chapters 5-8 demonstrate the original research which was conducted for the completion of this thesis. Chapter 9 includes a general discussion on the impact of the data collected and its utility going forward.

# 1 Clinical Background

The purpose of this chapter is to present the necessary understanding of neurovasculature, aneurysms, their presentation and treatment as a basis for the understanding of angiographic techniques and their technical complexity. This knowledge is necessary towards appreciation of the training specialists undergo and the barriers that exist within the current system, covered in subsequent sections.

## 1.1 Introduction

One of the earliest known references to brain aneurysms can be found in the writings of the ancient Greek physician Hippocrates, who described the symptoms of an aneurysm as "pains in the head" (Clarke, 1963; Smith et al., 1994). Later, in the 17th century, the Italian professor Marcello Malpighi used the microscope to demonstrate the finer capillary presence within the brain vasculature (Pearce, 2007) and create the foundations on which the 18$^{th}$ century Italian physician Giovanni Morgagni built the use of post-mortem examination to diagnose brain aneurysms (Vallee, 1998) with an evolving repertoire of cases involving ruptured arteries, hemorrhages and malformations recorded through the rest of the century. It wasn't until the nineteenth century that we first start seeing attempts to safely access and treat these lesions using the best methods of access understood at that time – open surgery. These procedures were incredibly risky, with high mortality and complication rates.

Over the years, numerous advances have been made in the treatment of aneurysms, including the development of endovascular techniques, which allow for the treatment of aneurysms via a catheter inserted into the blood vessels. These advances have greatly improved patient outcomes and have helped to establish interventional neuroradiology as an indispensable medical specialty (Baum & Baum, 2014; Pelz et al., 2021).

Today, neurosurgeons and neuroradiologists continue to build on the foundation using a combination of surgical and endovascular techniques to treat a wide range of neurological conditions. From the development of new surgical instruments and techniques to the use of advanced imaging technologies, the field of interventional radiology has seen numerous advances in recent years, and it continues to evolve and grow as new technologies and treatments are developed.

## 1.2 Anatomy

### 1.2.1 Neurovasculature

The brain is supplied with blood by two main arteries: the internal carotid artery and the vertebral artery (Figure 1). These arteries provide anterior and posterior circulation to the brain, respectively, and are essential for supporting the metabolic demands of the brain tissue.

The internal carotid artery arises from the common carotid artery, which is a major artery in the neck that supplies blood to the head and neck. The internal carotid artery enters the skull through the carotid canal and divides into the anterior and middle cerebral arteries, which supply blood to the front of the brain (Sethi et al., 2022; Wolman et al., 2022).

The vertebral artery arises from the subclavian artery, which is a major artery in the shoulder that supplies blood to the arm and chest. The vertebral artery travels up through the neck and enters the skull through the foramen magnum, where it joins with the other vertebral artery to form the basilar artery. The basilar artery then divides into the posterior cerebral arteries, which supply blood to the back of the brain.

In addition to the main arteries, the brain is also supplied with blood by a network of smaller arteries called the arterial circle of Willis. The circle of Willis is formed by the union of the internal carotid and vertebral arteries, as well as the posterior communicating arteries, which connect the posterior cerebral arteries to the internal carotid arteries. The arterial circle of Willis provides a backup blood supply to the brain in case one of the main arteries is blocked. Figure 1 demonstrates the manner in which the vascular supply is interconnected to supply the base of the brain.

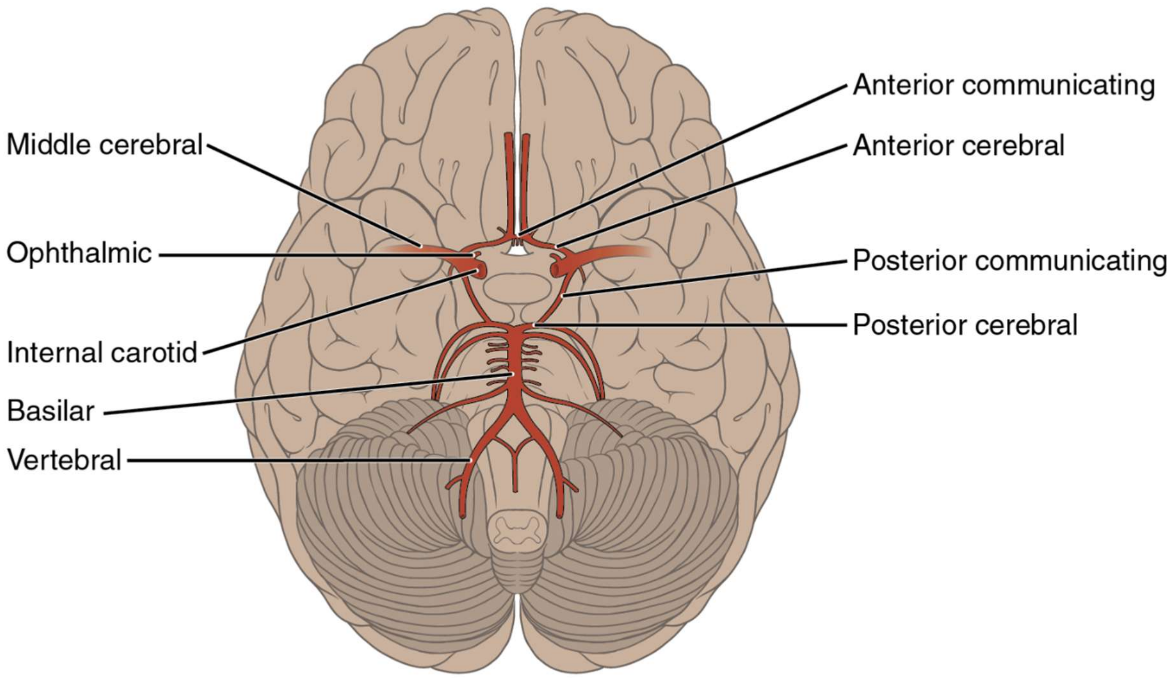


**Figure 1 – Major arterial supply to the brain**

**The major arteries supplying the brain from the neck are the internal carotid and vertebral arteries, suppling the anterior and posterior circulations, respectively. These arteries provide blood supply to the Circle of Willis where competing flows ensure saturated supply to cerebral tissue (Vanderah & Gould, 2020).**

### 1.2.2 Aneurysm Presentation

Aneurysms are abnormal bulges or dilations in the walls of arteries that result from structural abnormalities in the arterial walls (Aoki et al., 2009; Brisman et al., 2006; Chalouhi et al., 2013; Keedy, 2006). Aneurysms typically have three distinct parts: the neck, the body, and the dome (Figure 2). The neck is the area where the aneurysm attaches to the blood vessel wall, and it is typically the narrowest part of the aneurysm. The body is the main part of the aneurysm, and it is the area where the aneurysm bulges or protrudes from the blood vessel wall. The dome is the top part of the aneurysm, and it is the area where the aneurysm bulges the most.

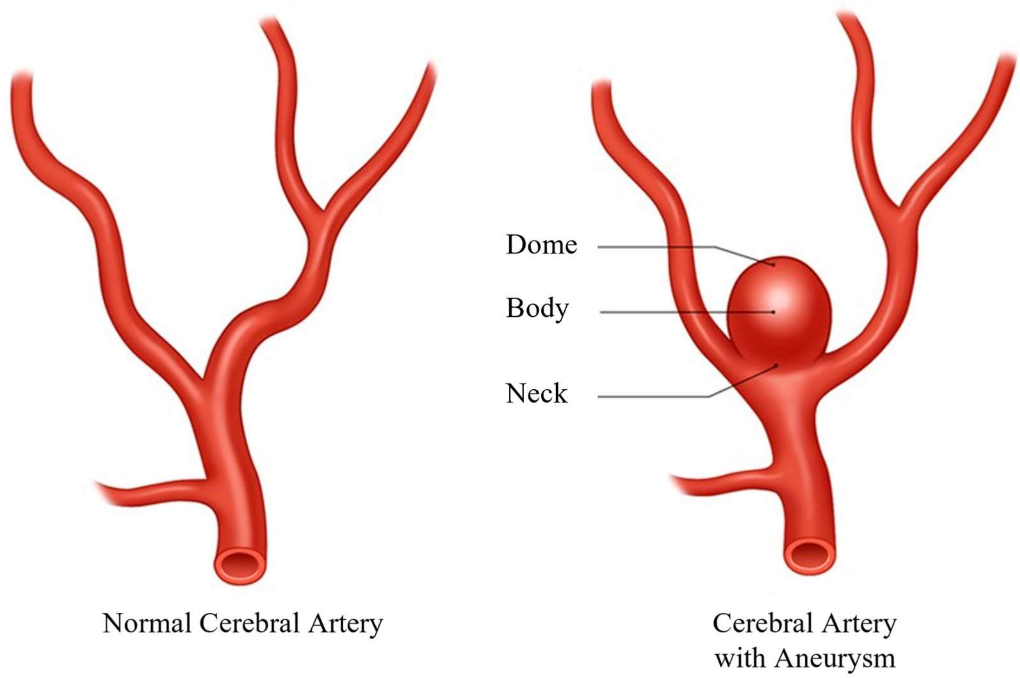


**Figure 2 – Aneurysm features**

**Typical presentation of a saccular arterial aneurysm can be seen at a major bifurcation point with its basic features, including the neck, body and dome. Adapted from (*The Aneurysm and AVM Foundation*)**

These three parts of an aneurysm can have different characteristics and clinical significance, and they are important to consider when assessing the risk and treatment of an aneurysm. For example, the neck of an aneurysm is important because it is the area that attaches the aneurysm to the blood vessel wall, and it can affect the stability of the aneurysm. A narrow neck may make an aneurysm more stable, while a wide neck, one with a dome to neck ratio less than 2 (Lazareska et al., 2018), may make it more likely to rupture (Hassan et al., 2005).

The body and dome of an aneurysm are also important, as they are the areas where the aneurysm bulges and protrudes from the blood vessel wall. The size and shape of the body and dome can affect the risk and treatment of an aneurysm, and they are often used to classify aneurysms into different types. For example, aneurysms that have a saccular shape, with a rounded sac-like protrusion, are more likely to rupture than other types of aneurysms and are more likely to be found at points of bifurcation within the Circle of Willis (Figure 3). On the other hand, aneurysms that have a fusiform shape, with a more elongated and diffuse appearance, are less likely to rupture and may not require treatment unless they are causing symptoms or are at high risk for rupture.

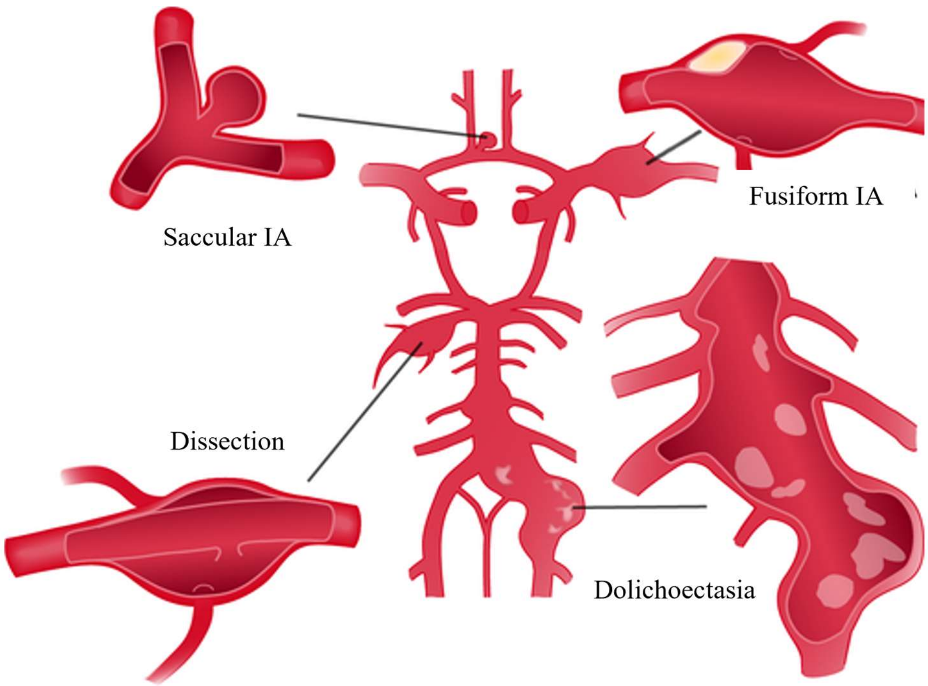


**Figure 3 – Types of aneurysms**

**The saccular intracranial aneurysm (IA) is often located at sites of arterial bifurcation, in contrast to the fusiform IA which bulges from arterial trunks (Kurtelius et al., 2019).**

## 1.3 Formation and Contributing Factors

The formation of brain aneurysms is promoted by a complex variety of factors which create abnormal or weakened blood vessels in the brain (Chalouhi et al., 2013). These weaknesses often involve collagen deficiency in the internal elastic lamina (Keedy, 2006), which leads to breakdown of tunica media and outpouching through tunica intima and adventitia (Austin et al., 1993; Stehbens et al., 1989) – the perfect recipe for saccular aneurysm. Handily, the tunica media's thinner presentation in small blood vessels and highly turbulent, diverging flow, leads to a higher prevalence of cerebral aneurysms (Figure 4).

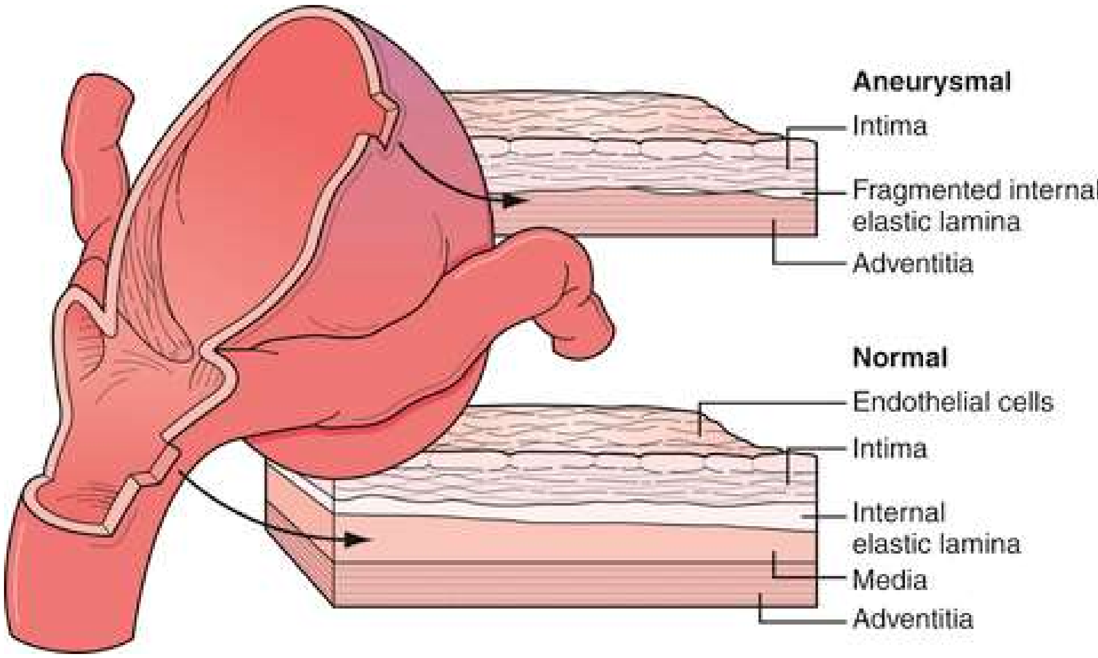


**Figure 4 – Layers of an aneurysm wall**

**The fragmented and thinned internal elastic lamina and absence of a tunica media creates a mix of highly sclerotic and weak patches (Eddleman et al., 2012).**

These factors can be present in a number of comorbidities (Aoki et al., 2009; Hasan et al., 2012) including genetic disorders such as polycystic kidney disease (Cagnazzo et al., 2017; Chapman et al., 1992; Fehlings & Gentili, 1991; Hadimeri et al., 1998; Matsumura et al., 1985; Pirson et al., 2002; Poutasse et al., 1954), arteriosclerosis (Daoud et al., 1963; Gore & Hirst, 1973; Graham et al., 1980; Pahlavan & Niroomand, 2006; Syed & Lesch, 1997), infections (Clare & Barrow, 1992; Kannoth et al., 2007; Pagiola et al., 2016; Peters et al., 2006), high blood pressure (Ellamushi et al., 2001; Fisher, 1972; Heuer et al., 2004; Phillips & Whisnant, 1992; Torii et al., 2007), diabetes (Adams et al., 1984; Arvanitakis et al., 2006; Tiehuis et al., 2008), and tobacco use (Canhão et al., 1994; Dasenbrock et al., 2018; Futchko et al., 2018; Ho et al., 2015; Woo et al., 2009).

The structure of the blood vessels in the brain may also contribute to the formation of aneurysms. The blood vessels in the brain are smaller and more delicate than those in other parts of the body, and they are more susceptible to damage and aneurysm formation (Brisman et al., 2006; Eddleman et al., 2012; Kurtelius et al., 2019). Consequently, the narrowing of vessels and their tortuous bifurcations contribute significantly to aneurysm formation through increased shear stresses and subsequent breakdown of the arterial wall (Bluestein et al., 1996; Ferguson, 1970, 1972; Khanafer et al., 2007; Sunderland et al., 2021).

Understanding these predictive factors about brain aneurysm formation, we can expect their distribution to be pocketed around smaller vessels with bifurcating and converging flow. The anterior circulation suffers from the highest prevalence of aneurysm formation, with anterior communicating artery and middle cerebral artery aneurysms making up more than half of all incidences (Figure 5). Interestingly, the pressures and flows experienced at anterior communicating and cerebral artery aneurysms make them much more likely to rupture and hemorrhage than middle cerebral artery aneurysms (Aarhus et al., 2009; Beck et al., 2006; Kivisaari et al., 2004).

**Size**

The size of an aneurysm is determined by measuring the external diameter of the sac. Intracranial aneurysms typically measure 6-7mm across the major sites of incidence, including AcoA, MCA, PcoA, and basilar tip (Jeong et al., 2009). This unruptured sweet spot is created by a paradoxical nature of ruptured aneurysm prevalence – larger aneurysms are more likely to rupture, except when they are under 5mm in diameter (Jeong et al., 2009; Kassell & Torner, 1983; Orz et al., 1997). Larger aneurysms have stretched the arterial layers to their limits, leading to more aggressive interventional strategies and less frequent unruptured presentation beyond 12mm. Conversely, small aneurysms are thought to be likely to rupture due to the high flow rate that they experience within their dome.

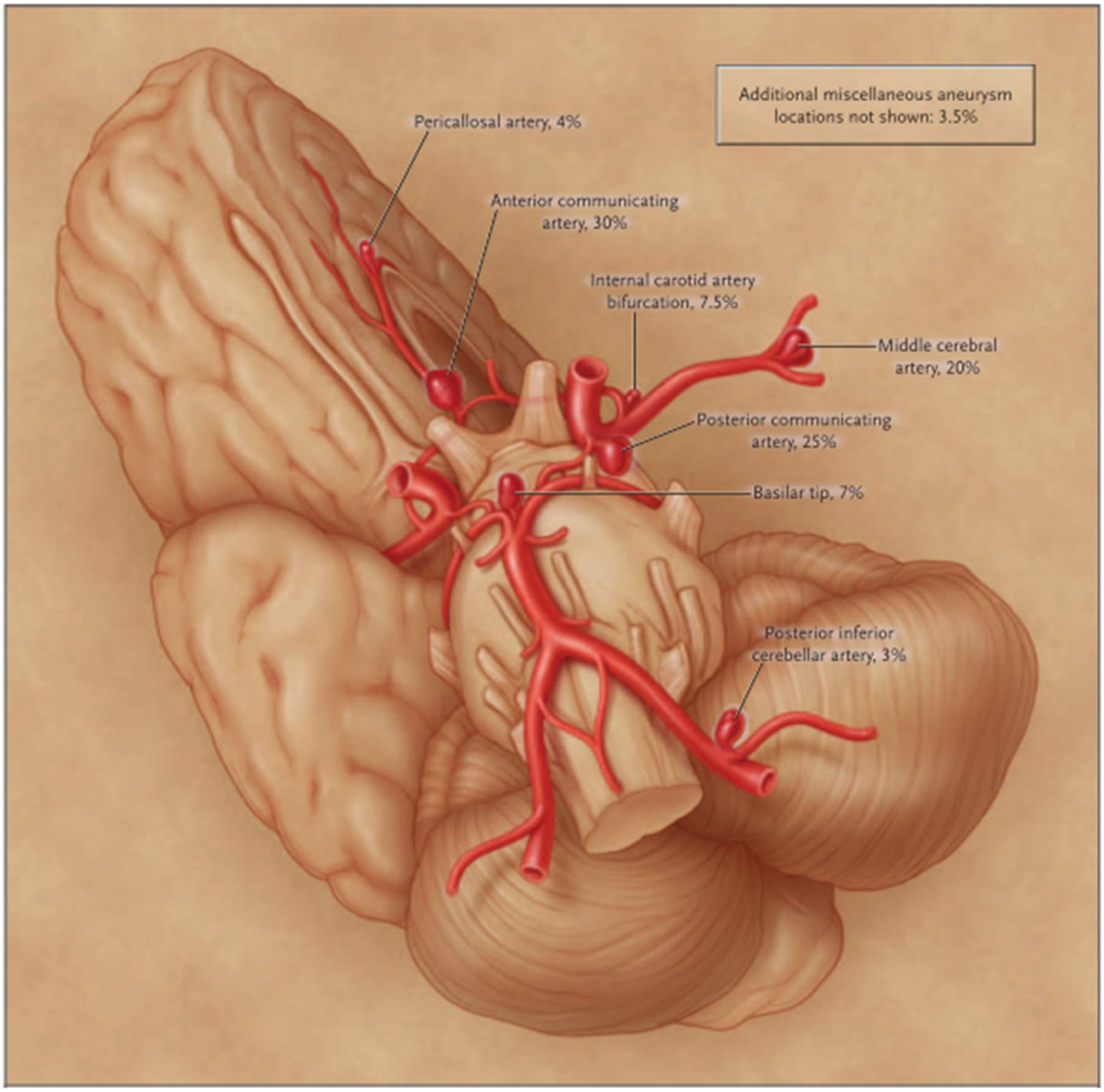


**Figure 5 – Intracranial aneurysm prevalence by location**

**Common locations of intracranial aneurysms and their prevalence identify (Brisman et al., 2006).**

## 1.4 Prevalence

The prevalence of these different types of brain aneurysms may vary depending on the population being studied. Small brain aneurysms are more common in younger individuals, while large brain aneurysms are more common in older individuals. Additionally, the prevalence of brain aneurysms is twice as high in women than in men due in part to hormonal factors, evidenced by incidence of brain aneurysms being higher in women during their reproductive years. In general, the overall prevalence of brain aneurysms is estimated to be between 2% and 4% of the population (Kim et al., 2021; Vernooij et al., 2007; Vlak et al., 2011; Wardlaw & White, 2000). These aneurysms often do not cause any symptoms, making them difficult to diagnose and estimating their prevalence through incidental findings (Vernooij et al., 2007; Vlak et al., 2011). Aneurysms smaller than 1 cm have a low risk of rupturing, especially in people without a history of subarachnoid hemorrhage (Chalouhi et al., 2013; Ferguson, 1972; Friedman et al., 2001; Wiebers, 2003). It is estimated that 50-80% of all aneurysms do not rupture (Brisman et al., 2006).

## 1.5 Clinical Presentation

It is important to note that not all brain aneurysms are symptomatic, and many individuals with brain aneurysms do not experience any symptoms or problems. In fact, most brain aneurysms are discovered incidentally, through imaging tests or other diagnostic procedures. This means that the true prevalence of brain aneurysms may be higher than estimates suggest, as many individuals with brain aneurysms may not be aware of their condition.

Symptomatic presentation of aneurysms can vary based on the aneurysm location, size, and state of rupture. Location of the aneurysm exposes it to vulnerable neuroanatomy, which can manifest itself in a variety of way in relation to the structures its impeding. Aneurysms arising from the ICA are much more likely to produce symptoms prior to rupture compared to those from the MCA (Raps et al., 1993), which tend to be discovered accidentally. The most common symptoms of unruptured intracranial aneurysms are headaches (Jeon et al., 2011; Levin, 2013; Wiebers, 2003), dizziness, ischemic cerebrovascular disease and cranial nerve deficits, such as loss of vision (Bhat & Sampath, 2011; Friedman et al., 2001; Kasner et al., 1997), pupil dilation and cranial nerve palsies (Bruce et al., 2007; Goldenberg-Cohen et al., 2004; Keane, 2010).

Rupture and hemorrhage of an intercranial aneurysm can lead to a wide range of severe neurological symptoms, such as weakness or paralysis on one side of the body, difficulty speaking or understanding speech, and thunderclap headaches (Linn et al., 1994; Polmear, 2003; Singhal, 2002; Wilkins & Goldman, 1994; Witham & Kaufmann, 2000).

If a ruptured aneurysm is not treated promptly, it can lead to serious complications and even death. Subarachnoid hemorrhage which occurs from largely due to intracranial aneurysms, accounts for 25% of all cerebrovascular deaths (Wardlaw & White, 2000), with most of them originating on the circle of Willis (Phillips & Whisnant, 1992).

## 1.6 Diagnosis

In recent years, there have been further advancements in the detection of brain aneurysms, including the development of more sophisticated imaging technologies and the use of computer-aided detection and analysis software to improve the accuracy and precision of diagnosis.

Specialized catheters, wires and micro-devices in modern cerebral angiography interventions build upon a rich history of catheter-based interventions, radiographic imaging advancements and open-surgical operations. Building on then-common techniques of using air and radio-opaque lipids to visualize brain tumours, Portuguese-born Egas Moniz was the first to specify the use of a non-oily, radio-opaque substance which could easily pass through capillaries to avoid formation of emboli or causing harm (Artico et al., 2017; Moniz E., 1927). This novel method of seeing the vasculature using an endovascular approach, termed “arterial encephalography”, marked a leap in humankind’s ability to assess and analyze the human body. Using cadavers, animals and human subjects, Moniz and his assistant Almeida Lima established a core foundation for the field, most importantly the implementation of sodium iodide as a rapid, pain-free contrast (Lima, 1973). Moniz used this novel contrast agent to discern the micro-vasculature within the brain in his cadaver studies, and later in 1926, Lima injected a sodium iodide-containing solution into patients undergoing surgery for cerebral aneurysm for the first time (Artico et al., 2017; Lima, 1973; Moniz E., 1927; Vallee, 1998).

By 1953, Swedish radiologist Sven Ivar Seldinger modernized the interventional radiology field with a method used to this day – the Seldinger technique – which uses a needle, guidewire and catheter to access the endovascular space (Seldinger, 1953).

### Diagnostic Angiography

Cerebral angiography is a medical procedure that involves using imaging techniques to study the blood vessels in the brain and neck. This procedure is typically performed in an Angio Suite - a specialized operating room fitted with imaging and endovascular tools necessary for minimally invasive procedures like cerebral angiography. In the Angio Suite, the patient will typically be given a sedative to help them relax and a local anesthetic to numb the area where the catheter will be inserted. A thin, flexible tube called a catheter is inserted into an artery, usually in the groin area. The catheter is then guided through the artery using a device called a fluoroscope, which uses X-rays to create real-time images of the inside of the body.

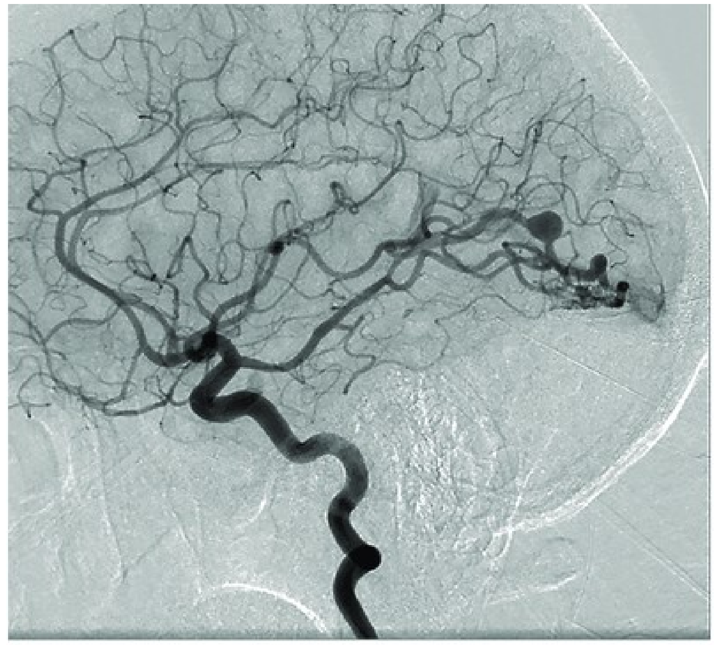

**Figure 6 – Cerebral digitally subtracted angiography**

**The subtraction of extravascular anatomy prior to contrast injection allows the interventionalist to more accurately see the contours of the illuminated neck vasculature on imaging (Luzzi et al., 2018).**

Once the catheter is in place, a contrast agent (a dye that shows up on the X-ray images) is injected through the catheter and into the blood vessels in the brain and neck. Rapid sequence films (a series of X-ray images taken in rapid succession) are taken as the contrast agent flows through the blood vessels. These images help the interventionalist assess the competency of the blood vessels and identify any abnormalities or blockages (Frizzell, 1998).

Diagnostic angiographic images are typically obtained using a technique called digital subtraction angiography (DSA). This involves taking a mask image of the relevant anatomy without contrast and subtracting from it the image of the anatomy with the contrast injected. This technique allows the radiologist to identify lesions, malformations, and stenoses by revealing important vascular detail without the presence of irrelevant extravascular anatomy (Figure 6) (Cowling, 2006).

There are four major advantages of using angiography in the diagnosis of intracranial aneurysms. Firstly, angiography can help differentiate between aneurysms and other lesions such as arteriovenous malformations (abnormal connections between arteries and veins). This is important because the treatment options for these different types of lesions can vary significantly. Second, angiography is generally considered to be a quick, accurate, and safe means of diagnosis for intracranial aneurysms. It allows the radiologist to clearly visualize the blood vessels in the brain and identify any abnormalities or blockages. Thirdly, angiography is able to produce more detailed and complete images of the blood vessels in the brain that can be helpful in identifying the size, shape, and location of an aneurysm, which can be important in planning treatment (Brisman et al., 2006). And lastly, angiography allows for a smooth transition from diagnostic imaging to interventional procedures for endovascular repair. These attributes work together to create a relatively accessible system with results good enough to make this process the gold standard for vascular diagnostics.

There are newer and more advanced methods of imaging the vessels which are superior in many ways, but to this day, fluoroscopic imaging remains to be the imaging of choice due to its relative availability across the world, facilitation of interventional techniques and low computing necessities (Burton & Bushnell, 2019; Yokoi, 2017). Magnetic resonance (MR) angiography and computed tomography (CT) angiography are two medical imaging techniques that can be used to visualize the blood vessels as well, but both techniques have their place and need. The advantage of MR angiography is that its use of magnetic and radio waves to produce images does not expose the patient to radiation (Aboulhosn, 2013; Brenner et al., 2007; Kiruluta & González, 2016), making it the preferred method for assessing children and pregnant women. MR angiography also excels in not requiring a contrast agent to visualize vessels and can provide very high-resolution imaging compared to the other modalities (Burton & Bushnell, 2019; Hartung et al., 2011; Morita et al., 2011). On the other hand, CT angiography provides much faster imaging which is preferred in emergency cases (Hagspiel et al., 2015; Rodallec et al., 2006) and can be used to guide interventional procedures, such as angioplasty and stenting.

However, the advantages of using these techniques only hold true as long as a highly trained interventionalist is able to maneuver around the major drawbacks of these tools. These caveats create a bottleneck in the acquisition of new skills as many of them have to be learned simultaneously. Firstly, the catheter tip is navigated through the endovascular lumen by gentle manipulation at the proximal end near the femoral access site (Čaluk, 2011). This requires not only the fine motor skills to create the appropriate pulls and bends in the catheter, but an ongoing translation of live 2-dimenstional fluoroscopic imaging to move the wire in 3 dimensions (Greig et al., 2020; Mitrović et al., 2013; Schimmel et al., 2016; Zuo et al., 2018). Concurrently, the interventionalist must be careful to limit their use of fluoroscopic imaging to limit radiation burns on the patient's skin, and therefore must at times choose when to disable the fluoroscopic imaging (Yokoi, 2017).

Angiography Risks and Complications

When it comes to cerebral angiography, patients can rest assured knowing that this procedure is both safe and effective. In fact, with a complication rate of less than 1% (Alakbarzade & Pereira, 2018; Fifi et al., 2009; Johnston et al., 2001; Leffers & Wagner, 2000; Lin et al., 2015; Willinsky et al., 2003), the chances of experiencing any permanent damage post-operatively are slim. Plus, with an infection rate of just 0.1% (Kelkar et al., 2013), the risk of infection is nearly nonexistent. So, what about the risk of death? Thankfully, that's also incredibly rare, with an incidence of just 0.14% (Kaufmann et al., 2007). All in all, cerebral angiography is a well-tolerated procedure with a high success rate. However, it's important to note that there are potential complications that can arise, and it's crucial to understand these and their rates.

One potential complication of cerebral angiography is allergic reactions to the contrast agent. These reactions can range from mild to severe, and include symptoms such as nausea, hypotension, bronchospasms and anaphylaxis (Bush & Swanson, 1991). The rate of allergic reactions to the contrast agent is generally low, with some studies reporting rates of less than 1% (Wang et al., 2012).

Another potential complication of cerebral angiography is radiation exposure. The x-rays used during the procedure can expose the patient to ionizing radiation, which can vary depending on the specific procedure and the imaging equipment used. If a threshold of radiation exposure is reached, clinical consequences, such as skin injury, may follow, correlating to the amount of exposure (Fletcher et al., 2002; Hertault et al., 2015).

A more serious complication of cerebral angiography is the risk of stroke. The procedure involves inserting a catheter into the blood vessels of the brain, and there is a small risk that the catheter could cause damage to or perforate the blood vessels. The risk of stroke during cerebral angiography is generally low, with rates of ischemic events staying under 2% (Dion et al., 1987; Johnston et al., 2001; Kaufmann et al., 2007).

## 1.7 Intervention

Diagnosis of aneurysms was only the first goal in the development of proper interventional techniques. Medical practice went through an array of techniques to treat aneurysms, from ligation of the ICA to forced embolization of blood inside the dome of the aneurysm (Lai & O'neill, 2017; Sosman, 1993). A more direct approach of wrapping the aneurysm using muscle from the thigh in the 1930s developed into a dominant technique of clipping the neck of the aneurysm (Louw et al., 2001). Presently, thanks to Guglielmi's development of platinum detachable coils in late 20th century, aneurysms can be treated without transcranial surgical approaches (Doerfler et al., 2006). These endovascular treatments are much more effective at treating unruptured aneurysms than surgical clipping (Byrne, 2006; Doerfler et al., 2006; Higashida et al., 2007; Maciej Serda et al., 2003; Meyers et al., 2010; Molyneux et al., 2005).

The first microsurgery performed on intracranial aneurysms date back to late 1960s. The first reported success of microsurgery was in 1969 by the French neurosurgeon Jean Cassegrain who managed to close a ruptured middle cerebral artery aneurysm with good results in a patient after having failed conventional surgical treatment. On April 2, 1973, Dr. James Hunt and Dr. Robert H. Fuisz performed the first aneurysm surgery with these techniques on a patient at the National Institutes of Health in Bethesda, Maryland.

Interventional Angiography


**Figure 7 – Angiography performed in an Angio Suite**
**An interventionalist in the middle of an interventional angiography procedure where they are stabilizing an aneurysm using endovascular coils, guided by angiographic imaging (*Philips: Direct to Angio Suite*).**

Interventional cerebral angiography is a medical procedure that uses imaging and specialized catheters to diagnose and treat conditions of the blood vessels in the brain. The procedure is performed by interventional radiologists, who are medical specialists trained in the use of imaging and minimally invasive procedures to diagnose and treat a variety of medical conditions (Figure 7).

Once the blood vessels of the brain are visualized, the interventional radiologist can use the catheter to perform a variety of interventional procedures (Dowd, 2021). These procedures can include embolization, which involves blocking or occluding the blood flow to a specific area of the brain, such as an aneurysm or arteriovenous malformation (Doerfler et al., 2006; Ellis & Lavine, 2014; Gupta et al., 2013). Other interventional procedures can include stenting, which involves placing a small metal mesh tube in the blood vessel to improve blood flow (Roguin & Beyar, 2010), and angioplasty, which involves using a balloon to widen a narrowed or blocked blood vessel (Pandey et al., 2013).

<u>Coiling</u>

During aneurysm coiling, the patient is typically sedated and a small incision is made in the groin area to access the femoral artery. A long, thin catheter is then inserted into the artery and guided through the blood vessels to the aneurysm. Once the catheter is positioned at the aneurysm, a small wire mesh or platinum coil is deployed through the catheter and into the aneurysm. The coil fills the aneurysm and blocks the blood flow, preventing it from rupturing (Figure 8) (Čaluk, 2011; Dowd, 2021; John J. Connors et al., 2004; Yokoi, 2017).

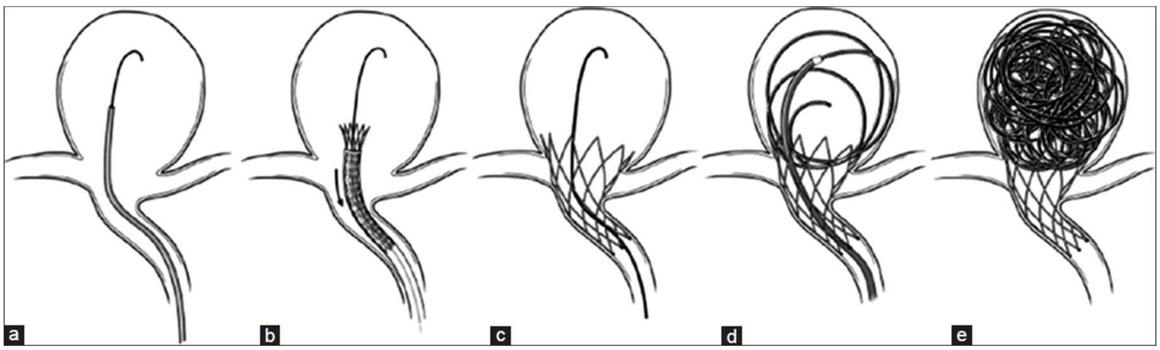


**Figure 8 - Aneurysm coiling basics**

**An electrolytically ligating coil is inserted into the lumen of the aneurysm and wound to create a stable mass which will reduce blood flow inside and reduce the likelihood of rupture (Padalino et al., 2013).**

Aneurysm coiling is typically performed by interventional radiologists, who are medical specialists trained in the use of imaging and minimally invasive procedures to diagnose and treat a variety of medical conditions. The procedure is typically performed under x-ray guidance to ensure accurate placement of the catheter and coil.

Although aneurysm coiling is generally considered a safe and effective treatment for brain aneurysms, the procedure can be challenging and difficult to perform (Dowd, 2021; John J. Connors et al., 2004; Mitrović et al., 2013; Schimmel et al., 2016; Yokoi, 2017). There are several factors that contribute to the difficulty of endovascular coiling, including the small size and delicate nature of the blood vessels in the brain (Brisman et al., 2006; Eddleman et al., 2012; Kurtelius et al., 2019), the complex anatomy of the brain, and the need for precise placement of the catheter and coil.

One of the challenges of aneurysm coiling is the small size and delicate nature of the blood vessels in the brain. The blood vessels in the brain are much smaller than the arteries and veins in other parts of the body, with diameters that can range from 0.3 to 4 millimeters (Gabrielsen & Greitz, 1970). This small size makes it difficult to navigate the blood vessels accurately without causing damage (Bluestein et al., 1996; Brisman et al., 2006; Eddleman et al., 2012). If damage to the vascular wall was to occur, the increased blood pressure makes rupture, and therefore damage to surrounding brain tissue, more probable.

Another challenge of aneurysm coiling is the complex vascular anatomy of the brain. The intricate network of blood vessels can be difficult to accurately visualize and understand using 2-dimensional imaging alone, requiring the use of more sophisticated imaging and added expectations of proficiency (Ahmad et al., 2019; Kramers, 2014; Zhong, 2007). This makes it difficult to identify the location of the aneurysm and to properly position the catheter and coil within its body.

A third challenge of aneurysm coiling is the need for precise placement of the catheter and coil. The success of the procedure depends on the ability to accurately place the catheter and coil within the aneurysm, and any deviation from the correct placement can lead to complications or failure of the procedure. The catheter and coil must be placed within the aneurysm in such a way that they block the blood flow to the aneurysm, but do not cause any damage to the surrounding blood vessels or brain tissue (Cloft & Kallmes, 2002; Griessenauer et al., 2014; Turk et al., 2013). This requires a high level of skill and expertise on the part of the interventional radiologist, and it can be difficult to achieve the necessary precision in some cases. Tools to assist with the patency and stability of the parent artery and the aneurysm, such as balloons and stents, may sometimes be crucial to establish appropriate placement of microcatheters and subsequent coils in awkwardly positioned or shaped aneurysms.

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# 2 Medical Training

The purpose of this chapter is to provide an overview of the training specialists receive to gain competencies in the skills and procedures covered in Chapter 1. This section provides evidence for the state of medical training today, standards and barriers which exist within this system, and competencies which are either already expected to be exhibited by the end of training or factors which are understood to affect their training performance.

## 2.1 Background

The history of neurointerventional specialization intertwines the responsibilities and technical capacities of neurosurgeons and neuroradiologists, with neuroradiologists more directly aligned with the skillsets required for the fellowship.

The history of neurosurgical residency can be traced back to the early 20th century, when the first neurosurgical training programs were established in the United States. Prior to this time, neurosurgeons were trained in general surgery programs, but the increasing complexity and specialization of neurosurgery led to the development of dedicated neurosurgical training programs. These early programs were designed to provide neurosurgeons with a broad-based education in neurosurgery, covering a wide range of surgical techniques and medical conditions.

Today, neurosurgical residency programs continue to provide training in the latest surgical techniques and technologies, as well as in the diagnosis and treatment of a wide range of neurosurgical conditions.

Neuroradiology has evolved alongside neurosurgery and has staked its necessity in the cornerstones of imaging use and progress. As a medical specialty, neuroradiology involves the use of imaging techniques, such as CT, MR imaging, and fluoroscopy to diagnose and treat diseases of the brain, spine, and head and neck (R. Higashida et al., 2000). Much like neurosurgery, this field really started to gain complexity in the early 20$^{th}$ century with the development of new instrumentation and techniques. In 1913, German radiologist Hermann Schultze used x-ray imaging to identify a brain tumor in a patient, marking the beginning of the use of radiographic techniques in neuroradiology. In the decades that followed, the development of new imaging technologies, including CT scanners in the 1970s and MRI in the 1980s, revolutionized the field and became essential tools in neuroradiology practice.

The increasing reliance on imaging technologies in modern medicine has led to a growing demand for neuroradiologists, who play a crucial role in the diagnosis and treatment of a wide range of neurological conditions including brain tumors, stroke, aneurysms, and spinal disorders, among others. Neuroradiologists work closely with neurologists and neurosurgeons to develop comprehensive treatment plans for their patients.

As these technologies have evolved, so too has the training and practice of neuroradiologists. In the United States and Canada, neuroradiologists typically complete a four-year residency in diagnostic radiology followed by a one- to two-year fellowship in neuroradiology, during which they receive specialized training in interventional procedures (Day et al., 2017; R. Higashida et al., 2000). Neuroendovascular programs typically require the completion of residency in either neurologic surgery or neuroradiology, including a preparatory year in neuroendovascular surgery/interventional neuroradiology (Gasco et al., 2010; R. Higashida et al., 2000) prior to admitting for an endovascular fellowship.

## 2.2 Master Apprentice Model

The current model for medical education was developed over a century ago, with little regard for the needs of modern-day learners (Bartoletti & Meyer, 2020; Evans et al., 2016). Today's learners have different learning needs than those who were educated in past centuries; The model needs to be re-evaluated and modified to meet the needs of the modern learner.

The Master-Apprentice model involves a more experienced physician (the "master") training a less experienced physician (the "apprentice") through hands-on experience and observation. This structure, although foundational to our understanding of the medical education system, is one which hinders learners from innovating due to their dependence on knowledge from their elders their teaching style (Armstrong & Barsion, 2013; Evans et al., 2016; Lucey, 2013; Ludmerer, 2004) and ability to demonstrate technique. The apprentice may not have the opportunity to see a wide range of cases or gain experience in all aspects of the specialty which can be particularly problematic in fields where cases are rare or complex. The master-apprentice model can be timeconsuming for both the master and apprentice, as the master may need to devote significant time and energy to teaching and the apprentice may have less time to focus on their own learning and development. This can be particularly challenging in busy clinical environments where time is limited.

This model exists at the heart of medical education to this day, and without proper complementary training and adjustments, becomes a roadblock in a system overseeing larger numbers of treatable patients, strict working conditions and performance standards, and ever-increasing subsets of skills, tools and procedures making up each specialists repertoire.

## 2.3 Training Standards

Training standards for medical residents are typically maintained through a combination of institutional policies, accreditation standards, and professional guidelines. At the institutional level, medical residency programs are typically responsible for establishing and maintaining standards for the education and training of their residents. This may include setting goals and objectives for the program, developing curriculum and learning materials, and establishing policies and procedures for evaluating and assessing residents' progress.

Accreditation standards also play a role in maintaining training standards for medical residents. Accrediting bodies, such as the Accreditation Council for Graduate Medical Education (ACGME) in the United States, establish standards for the quality and content of medical residency programs. These standards include the selection and supervision of residents, the quality of the educational experience, and the resources and facilities available for training. Medical residency programs that meet these standards are accredited, which is important for ensuring the quality and consistency of the education and training provided to residents. In recent years, the training of specialists has become more formalized and standardized due to a number of factors, including advances in surgical technology, the increasing complexity of surgical procedures, and concerns about patient safety.

One of the key changes in medical residency training standards has been the increased emphasis on competency-based education (Bourgeois et al., 2015; Long, 2000; Potts, 2016; Ryan et al., 2021; Wentzell et al., 2019; Yoon et al., 2019). This approach focuses on the development of specific skills and knowledge that are necessary for success in practice, rather than simply requiring a certain number of years of training. This shift has led to a greater emphasis on measurable outcomes and the use of assessment tools and evaluation methods to track progress and identify areas for improvement.

### 2.3.1 Competency-based medical education

Competency-based medical education (CBME) is a teaching and learning approach that focuses on the development of specific knowledge, skills, attitudes, and behaviors that are necessary for successful practice in the medical field. CBME offers a number of potential benefits compared to traditional medical education approaches. One of the main benefits of CBME is that it allows trainees to progress at their own pace, based on their individual learning needs and abilities. This can be particularly beneficial for trainees who have prior experience or knowledge in a specific area, as they can demonstrate their competencies and move on to more advanced training without having to repeat material that they have already mastered.

This allows trainees to develop a wide range of competencies in a standardized manner, including technical skills and knowledge, but also non-technical skills such as communication, teamwork, leadership, and professionalism (Mirza & Athreya, 2018, Munro et al., 2016). This approach to medical education helps to ensure that trainees are well-prepared for the complex and diverse challenges of medical practice, and it allows them to develop a well-rounded set of skills and abilities that are essential for success in the field. Moreover, this also prepares trainees for the high-performance standards that are set by their specialty to provide the highest level of care possible.

For medical educators and training programs, CBME can provide a more structured and systematic approach to teaching and learning, allowing educators to focus on specific competencies and assess trainees' progress and achievements more accurately (Munro et al., 2016). This can help to ensure that trainees receive the necessary education and training to meet the standards and expectations of the medical profession, and it can provide a more objective and transparent way of assessing trainees' competencies and readiness for practice. A more flexible and adaptable approach to medical education allows educators to tailor the training to the needs and goals of individual trainees and to respond to changing requirements and standards in the medical field (Munro et al., 2016). This can help to ensure that trainees receive the most relevant and up-to-date education and training, and it can support the continuous development and improvement of medical education programs.

### 2.3.2 Development of Technical Competence

Technical competence is a crucial factor in the success of surgical procedures and the safety of patients. It is defined as the ability to perform surgical techniques with proficiency and accuracy, and it is essential for surgeons and interventionalists to continually develop and maintain their technical skills.

The impact of technical competence on surgical outcomes has been studied extensively, especially with its impact on decreasing the number of procedural errors (Bann et al., 2005; Cuschieri, 2005; Dankelman et al., 2003; Fried et al., 2005; Hamdorf & Hall, 2000; Moorthy et al., 2003; Watters & Truskett, 2013) and lowering rates of complications to which they were contributing (Cuschieri, 2005; Julià et al., 2014; Nealon, 1971; Stulberg et al., 2020; Tou et al., 2020).

There are several factors that can affect a surgeon's technical competence. These include the complexity of the procedure, the surgeon's level of experience, and the availability of appropriate training and education. Surgeons who are well-trained and experienced are more likely to have high levels of technical competence, but even experienced surgeons can benefit from continued training and education to maintain and improve their skills.

Surgical residents who receive better training and more practice in operating room procedures generally have higher levels of technical competence to be able to perform operations with improved efficiency (Hamdorf & Hall, 2000; Moorthy et al., 2003; A. M. Spiotta et al., 2018). This competence is further accelerated in surgeons who perform a greater number of case types and have additional training in new procedures.

In addition to the impact on patient outcomes, technical competence is also important for the surgeon's professional satisfaction and well-being. Surgeons who are confident in their technical skills are more likely to feel fulfilled and satisfied in their careers, and are less likely to experience burnout (Ahmed et al., 2015). Regular feedback with a patient simulator has been shown to improve a trainee's skill far more than training on a non-simulated patient (Rice et al., 2014).

Motor skills

Motor skills are physical abilities that involve the coordination and control of movement, and are essential for a wide range of activities, including daily tasks, sports and physical activities, and skilled movements, such as those involved in surgical procedures (Silvennoinen et al., 2009; Wulf et al., 2010).

In the context of surgery, motor skills are important for a number of reasons. First, surgeons need to have well-developed motor skills in order to perform complex and precise movements with their hands and other surgical instruments (Silvennoinen et al., 2009). These skills are essential for surgical procedures, as they allow surgeons to navigate and manipulate the surgical environment, and to perform delicate and precise movements.

Additionally, motor skills are also important for other aspects of surgical practice, such as surgical planning and decision making (Wulf & Shea, 2002; Yule et al., 2006). Surgeons need to be able to assess the surgical environment quickly and accurately (Spruit et al., 2014), and to make judgments about the best course of action based on their observations and knowledge of surgical procedures. This requires a combination of cognitive and motor skills, and it is essential for successful surgical practice.

Visuo-spatial skills

Visuospatial skills are cognitive abilities that involve the perception, interpretation, and manipulation of visual information in space. These skills are essential for a wide range of activities, including navigation, spatial reasoning, and visual problem-solving (M. C. Linn & Petersen, 1985).

Visuospatial skills are closely related to visual perception, which is the process of interpreting and organizing visual information from the environment (Luursema, 2010; Maurice-Ventouris et al., 2021). Visuospatial skills allow individuals to use visual information to understand and navigate the spatial layout of the environment, and to solve problems that require visual analysis and spatial reasoning.

Studies have shown that visuospatial skills are important for a wide range of activities, including navigation and wayfinding, spatial orientation, and spatial problem-solving (Luursema et al., 2010; Luursema, 2010; Nguyen, Mulla, et al., 2014; Paul et al., 2023; van Herzeele et al., 2010). These skills are also important for many aspects of daily life, such as reading maps and diagrams, arranging objects in space, and playing sports and other spatial games (Linn and Petersen, 1985).

Furthermore, research has also shown that visuospatial skills are related to other cognitive abilities, such as attention, memory, and problem-solving. These abilities are often used in conjunction with visuospatial skills to solve complex problems and perform tasks that require spatial reasoning (Linn and Petersen, 1985).

### 2.3.3 Visuospatial Skills and Minimally Invasive Procedures

Visuospatial ability, or the ability to perceive and interpret visual information in relation to spatial relationships, is an important skill for surgeons performing minimally invasive procedures. Mental rotation ability is a cognitive ability subset that is involved in mentally rotating objects to understand their appearance from different points of view, and it has been shown to be an important predictor of success in surgical training and practice. Spatial visualization is another subset of skills which involves the ability to understand 3D objects through 2D representations (Vajsbaher et al., 2018), an incredibly fundamental skill for interpretation of anatomy on 2D representations (Roach et al., 2021; Van Nuland & Rogers, 2016).

Studies have found that individuals with higher levels of mental rotation ability tend to perform better on surgical skills assessments and simulations, and they are more likely to be successful in surgical training programs (Abe et al., 2018; Hedman et al., 2006; Mistry et al., 2013; Rogister et al., 2021.; Schlickum et al., 2011). This relationship between mental rotation ability and surgical performance may be due to the fact that mental rotation ability is an important cognitive ability for spatial reasoning, which is essential for many aspects of surgical practice, including surgical planning, navigation, and execution of surgical procedures.

Additionally, mental rotation ability may also be related to other factors that are important for surgical performance, such as manual dexterity, attention to detail, and problem-solving abilities. Visuospatial ability has a critical role to play in novice performance (Luursema, 2010; Paul et al., 2023; van Herzeele et al., 2010), so much so that many have suggested it can be used to predict (Paul et al., 2021) and eventually select for performance (Paul et al., 2023; Wanzel et al., 2002), much like is already being done in dentistry (Dailey, 1995; J. Graham, 1972).

It should be noted that this relationship is strongest earlier in training, as the beneficial effects of high competency on these skillset has a diminishing rate of return in more experienced clinicians (Keehner et al., 2004).

## 2.4 Training Barriers

Despite the importance of fellowship training in ensuring that interventionalists are well-prepared to provide safe and effective care to patients, there are several barriers that can prevent them from receiving adequate training, including financial constraints, proficiency timelines, and pedagogical shortages.

The cost of training is a significant financial barrier, as neurosurgical and neurointerventional residency programs require a significant investment of time, money, and resources. When residents are being trained in the operating room, the procedures typically take much longer (Castillo et al., 2013; Pförringer et al., 2017), and escalate the operating room costs to the hospital, which can easily range $10-15 per minute (Allen et al., 2016; Kaye et al., 2015; Park & Dickerson, 2009) and constitute up to 40% of a hospital's operating budget (Healey et al., 2015).

The cost of angiography suite procedures, which are commonly used in neurosurgery, is also expensive, averaging at $690 per hour (Janne D'Othée et al., 2006), which can come at a significant expense compared to hybrid or simulation-based training (Maertens et al., 2018).

The time it takes to train is a logistical barrier, as there is a limited number of specialty training programs in the United States and a limited number of available training positions within these programs (Ekhator & Rak, 2022; Emin et al., 2019; Killen & Gosbell, 2013; Yun et al., 2019). This can create competition for training positions and make it difficult for aspiring neurosurgeons and radiologists to secure a training position and complete the necessary education and training. Cerebrovascular fellowships, which are highly sought after, especially in low-income countries where access to advanced tools may be limited (Robertson et al., 2020), can further contribute to the bottleneck in the training pipeline.

The amount of mentorship trainees receive is another logistical barrier, as neurosurgical training programs are known for their high workload and long hours, which can lead to fatigue, poor mental health, and reduced training quality (Hui et al., 2018). Survey data has revealed that program directors estimate that 50% of neuroendovascular fellows are not able to formulate appropriate treatment plans, and as many as 79% are not sufficiently familiar with angiographic equipment (Chalouhi et al., 2015). There is also a limit on the amount of time trainees can spend with their mentors making clinical decisions (Miller et al., 2019). The ACGME has imposed a weekly limit of 80 hours for trainees to prevent exposing patients to poor care, as most interventional radiology (IR) procedures are performed under moderate sedation and patients may be aware of and remember all the events of the angiography suite. Patients may also request the exclusion of a trainee from their healthcare team altogether (Dutta et al., 2003; Graber et al., 2005).

## 2.5 Medical Errors

Medical errors are a pervasive and deadly issue, with an estimated 100,000 deaths in the United States each year (Pham et al., 2012; Shojania & DIxon-Woods, 2016; Sox & Woloshin, 2000), costing more than 17 billion dollars a year (van den Bos et al., 2017). In fact, the rate of medical errors is so significant that it is considered to be the eighth leading cause of death in the country (Bernstein et al, 2003). When patients are in a life-threatening emergency, or when doctors are just beginning to learn a new procedure, the likelihood of misdiagnosis or misinterpretation increases (Caranci et al., 2015; Guly, 2001). These errors can have devastating consequences for patients and their families.

Neurointerventionalists often encounter both technical and cognitive errors during the treatment of unruptured intracranial aneurysms. The most common type of complication in this field is vascular access site complications. A study of surgical trainees revealed a surprising amount of variation in the number of errors committed by the trainees (Tang et al., 2005). Neuroradiologists also face their own challenges, with a 2.0% rate of clinically significant discrepancies in their imaging (Babiarz Yousem et al., 2012). All in all, errors and complications are unfortunately a common occurrence in the world of neurointerventional procedures (Goyal et al., 2021) and their reduction needs to be constant pursuit within the field.

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# 3 Simulation

This chapter aims to cover the origins and use of simulation in medicine, the forms its takes within a variety of modalities, and its present-day implementation in endovascular training. This section combines the foundations of clinical practice and training standards to provide context for the importance of a concentrated simulation-based complement to our current educational systems.

## 3.1 Background

The use of simulation as an educational tool is deeply engrained in history; in fact many primitive forms of simulation can be overlooked as such due to their contrasting simplicity over how simulation is recognized in present day. The military has been perhaps the most famous practical implementer of original simulation, recreating chess-like warfare scenarios in order to generate a risk/benefit analysis (Bradley, 2006; Perkins, 2007). Although military uses for simulation are the cornerstone for its progression, other fields have also taken advantage of the benefits of simulation for centuries.

It is clear the industries that involve a high amount of risk, such as the military and aviation, are the industries that are pioneers in the field of simulation (Ziv, Small, & Wolpe, 2000) due to its increasing value. Other fields have taken notice and have used simulation for planning, risk reduction and control (Ziv et al., 2000) - transportation, legal proceedings, professional sports, homicide investigation training, and construction (Ziv et al., 2000). The medical field, which includes a high amount of risk, has been stimulated into incorporating modern simulation methods into training due to advances in medical care, shifts in tolerance towards error and injury reduction (Ziv et al., 2000) and progression towards cost-reducing methods.

In medicine, dissection of body organs and tissues, a form of simulation, was studied in sacrificed animals since the 3rd century and in human cadavers since the 13th century (Frati et al., 2006). It is these processes that have given rise to modern cadaveric dissections that are being used to educate not only gross-level anatomy, but also procedural skills for various medical specialists. For example, training of endovascular skills has been aided with the use of synthetic models, anesthetised animals and human cadavers (Neequaye et al., 2007).

During the late 1960s and early 1970s, the incorporation of computers in patient simulator development grew in stride with advancements in processing power. Utilization of these computer-based simulators was relatively limited until the 1980s when simulations became more complex. During that time period, researchers developed patient simulators for a variety of scenarios including general practice settings and anesthesiologists (Perkins, 2007).

Switching from the simple absorbent cotton swab to electronic devices such as nasal aspirators and tracheal tubes for patient simulations is a large leap in training capability. The ease of use, better feedback, and patient control make these kinds of simulation more beneficial than old-school swabs, however, these simulators do not mimic all features of tissues and organs.

In these areas the need for more realistic simulators is unquestioned. These devices would allow the users to perform procedures as if they were being done on a real patient. It is also likely that future simulations will be able to follow more than one trainee and provide more flexibility in learning experiences. As this technology progresses it will likely replace some current training options.

The ability for simulation to improve the learning and transfer of skills is important because this is a way that current hospital staff can be trained by an already established body of knowledge (Kahol et al., 2010). The use of these systems will improve the information provided to medical students, allowing a larger body of knowledge to be learned by trainees than they would otherwise be able to see in time (Ziv & Ben-David, 2011).

## 3.2 Types of Simulation

Simulation-based training is an important tool that is used to help train surgeons and other healthcare professionals in a safe and controlled environment. Simulation-based training uses a variety of different simulation technologies and techniques to create realistic and lifelike simulations of surgical procedures and other medical scenarios. These simulations provide a valuable learning experience that can help trainees develop their skills, knowledge, and decision-making abilities.

A variety of forms of simulation are used for training purposes in medicine. The simplest of methods utilize manikins and cadaveric specimens for psychomotor skill and basic cognitive education (Ziv et al., 2000). Manikins, for example, are established in First Aid training as a low-cost, realistic solution to providing effective skill acquisition in life support maneuvers. Cadaveric models are another simple method of simulation, commonly used to teach anatomy and various clinical procedures, such as breast examinations and anaesthesia administration (Ziv et al., 2000). However, these models can be expensive for the amount of use they provide, can be limited in availability, and vary in quality based on fixation techniques used (Ziv et al., 2000).

Physical simulators vary widely in cost and realism, but are routinely used in skills centres to teach a wide array of practical procedures from venepuncture and wound closure to thoracostomy (R. Kneebone, 2003; R. Kneebone & ApSimon D, 2001). Technological advances in physical materials has vastly improved the realism of physical simulation which can provide a realistic way of practicing the technical skills needed for minor surgical procedures. Standardized patients are also a form of simulation, however, unlike models that teach technical skills, they are used to train communication skills with patients and have become a necessary component of medical curricula.

With the technology that is being developed today, it is possible to train skills in virtual environments. Virtual reality (VR) systems allow trainees to interact with a 3D digital world in a human-computer interface (Gorman et al., 1999). Through the use of hand tracking devices, motion suits, and haptic feedback mechanisms, VR allows for complete immersion into the environment, facilitating the acquisition of skills (Greenleaf, 1996). With new technologies being developed continuously, this method is become more immersive and clinically relevant as a training tool.

A category of computer-driven task/procedural trainers is also growing rapidly (Ziv et al., 2000). These systems use realistic, interactive cues, such as hapsis and audiovisuals, to guide the user through a variety of computer-driven clinical scenarios (Perkins, 2007). A famous example of this form of simulation is the Harvey Cardiology Patient Simulator, which presents cardiovascular training scenarios to improve efficacy over traditional methods of teaching alone (Issenberg et al., 1999). This type of simulation is also widely distributed for training of diagnostic and interventional endovascular skills in angiography through commercial systems such as the ANGIO Mentor and VIST.

## 3.3 Benefits of Simulation

Simulation-based medical education (SBME) has proven to be a highly effective teaching method, boosting confidence, and honing crucial skills such as decision-making and reflective learning in students (Ziv et al., 2005). In fact, those who have extensively utilized simulation have even outperformed their counterparts with little to no experience with the technology (Ziv et al., 2005). Not only does SBME complement traditional approaches like bedside teaching and lectures, it also provides a safe space for learners to make mistakes and learn from them through an error management system (Ziv et al., 2005). This not only enhances technical proficiency but fosters a culture of excellence in the field of medicine (Ziv et al., 2005). In addition, simulation has been shown to foster the development of decision-making skills and facilitate reflective learning and debriefing (Ziv et al., 2000), essential components of professional maturity. It is essential to understand how these skills can be applied in real-world situations, and the simulation design process should be carefully considered when creating a simulation.

There are numerous studies enhancing surgical skills through simulations. Specifically, surgical simulations increase trainee confidence (Champion & Gallagher, 2003; Gordon & Buckley, 2009; R. L. Kneebone, 2009; Stefanidis, 2010), and has been shown to impact the quality of surgical teaching assessed by building student confidence in their decision-making abilities (Bevilacqua et al., 2019; Blue et al., 1999; Servais et al., 2006). Though there are benefits to surgical simulation training, there are also drawbacks. For instance, it has been shown that surgical proficiency is not always transferred from a simulator to the operating room (Stefanidis, 2010). Despite this concern, there is evidence that simulation training leads to favorable patient outcomes when compared with traditional training methods (Cook et al., 2011; Lorello et al., 2014; Okuda et al., 2009; Ribeiro et al., 2018; Zendejas et al., 2013).

Simulation-based medical education is a valuable tool for surgical trainees looking to balance learning and practicing technical skills without jeopardizing patient safety (Gorman et al., 1999). As a safe and controlled alternative to live training with patients, simulation enables physicians to develop their skills in a more enjoyable and less invasive way (Gorman et al., 1999). It also provides consistent feedback and the opportunity to review and build upon existing knowledge.

A central component of SBME is error management (Ziv et al., 2005). Simulation allows for learning from errors in a risk-free environment, which can improve long-term retention and transfer of skills when practicing high-risk procedures without psychological stress (Kahol et al., 2010; Lopreiato & Sawyer, 2015; Ziv et al., 2005). As simulation technology improves and becomes more realistic and safe, it has the potential to improve patient safety by exposing trainees to clinical scenarios they may not encounter when first practicing on actual patients (Kahol et al., 2010).

Models of surgical performance can inform the design of simulation-based training programs in various ways, such as predicting and identifying errors, providing learning objectives and aids for debriefing sessions, and informing the design of simulated surgical interventions, however, there currently exists no system for predicting surgical errors through simulation, and only recent publications have hinted at the need for such systems (Boyle et al., 2011; Harris, 2017; Satava, 2005).

A simulated surgical ecosystem can provide a zero-risk learning environment, which, through simplified procedures, can effectively establish skills in trainees – the more realistic the simulator, the more transferrable the skills (Sturm et al., 2008). Furthermore, surgical simulators are increasingly being used to train surgeons to establish competency in new surgical techniques (Hsu, Surowiec, et al., 2004).

Simulation training provides the opportunity to train mechanical skills on rare, but vital cases that the trainees may not otherwise see in their training, a condition that is viable in fields such as critical resuscitation (Smith et al., 2010). The difficulty of cases can also be graded in order to facilitate learning (Pellegrini, 2006; Spiotta et al., 2012) and can be taught complementary to apprenticeship experience. Simulation in medicine is now widely used, especially in surgical education. There are several clinical applications that rely on simulation, such as laparoscopic surgery (Wang et al., 2008) and robotic surgery (Panait et al., 2014).

The hierarchy of cognitive tasks is well established in cognitive psychology and it serves as a useful framework to assist with designing models of cognition, notably computer simulations. Despite this, it has been little explored in simulations of surgical training. The rationale is that the cognitive tasks required to successfully complete simulations need to be represented in order for the system to be useful (Hudson, 2008).

Trainees have found that simulation is useful for achieving learning objectives and improving interspecialty collaboration and skill transfer through cross-training (Nelson et al., 2014). The ability for simulation to enhance learning and skill transfer is important because it allows current hospital staff to be trained based on an established body of knowledge (Kahol et al., 2010). This can provide trainees with access to a larger body of knowledge than they would otherwise be able to learn in a given time frame (Ziv & Ben-David, 2011).

Simulation-based approaches to training have been found to increase the speed at which physicians gain clinical experience and to reduce error rates (Gardner & Rich, 2014; Pham et al., 2012; Tang et al., 2005; Ziv et al., 2005). These results highlight the importance of simulation-based training in clinical settings. In times of uncertainty, such as during the COVID-19 pandemic, an incorporated simulation-based training program can provide flexibility and allow training to continue uninterrupted. One example of this is a team that implemented endovascular simulation to provide both guided and self-directed training scenarios (Kesselman et al., 2020). Simulation-based training can also provide a zero-risk learning environment for establishing skills in trainees, with the added benefit that the more realistic the simulator, the more transferable the skills (Sturm et al., 2008).

One of the common criticisms of simulation training, especially in terms of VR simulation, is that it can be expensive to purchase the simulators (Gasco et al., 2013; Guedes et al., 2019). However, the aim of simulation training is to reduce the inherent errors that are associated with a procedural learning curve that could potentially harm the patient. Medical errors can result in lifelong morbidity or mortality to the patient, and can be extremely costly to a healthcare system, both in the cost of added interventions to remedy the error, and the associated litigation costs that may occur (Weingart et al., 2000). Therefore, simulation may provide a cost efficient way of training junior surgeons (Sutherland et al., 2006).

## 3.4 Limitations of Simulation

Simulation is a valuable tool for teaching and learning, but it can also impart bad habits if it does not accurately reflect real events. This is particularly true in fields where the consequences of mistakes can be severe, such as aviation, healthcare, and law enforcement. This can be exacerbated by simulations that do not accurately reflect the complexity of the procedure, and create a false sense of confidence in the trainee (Gaba, 2007). It is important for those designing and using simulations to carefully consider the limitations of the technology and ensure that it accurately reflects real-life scenarios. This can help prevent the development of bad habits and training scars, which can significantly impact the patient's quality of life.

A simulator also requires a significant initial expense that some facilities could not justify, especially if the audience and training modalities are limited (Ziv et al., 2000). As well, there is a need for technical and professional support in order to maintain the efficacy of the machine (Nelson et al., 2014). One of the challenges with surgical simulators is the current lack of standardized training syllabus, and the need to teach the skills of others (Ziv et al., 2000).

More specifically, it has been argued that surgeons are not always the best teachers for surgical training (Simpson et al., 2020) due to their lack of teaching and communication skills. Multiple studies have shown that there are effective teaching strategies to be used in simulation-based training (Aggarwal et al., 2010; Anderson et al., 2008; Chernikova et al., 2020; Kaufman & Ireland, 2016; Lane & Mitchell, 2013; Lateef, 2010); however, adherence to these strategies is limited. A possible way around this problem could be to have a blended learning approach, making use of autonomous and supervised virtual reality training.

Most importantly, the trainee must be able to relate what they are doing in the virtual environment to a real-life procedure in order to really learn from it. This means that a simulator should not be too remote from reality. However, this is dependent on setting the correct level of task difficulty by taking into account the trainees skills and their competencies, and this is difficult (Ahissar & Hochstein, 1997; Borkett-Jones & Morris, 2010; Brydges et al., 2008; Hughes et al., 2013; Moorthy et al., 2003) or expensive to do accurately.

## 3.5 Simulation in Interventional Radiology

The use of simulation-based training can allow neurointerventionalists to gain the necessary clinical experience in a relatively short period of time. In doing so, they can diagnose and treat neurological disorders much more efficiently than with conventional learning approaches. Despite these advantages, there are challenges that present themselves when using simulation-based training in the field of interventional radiology. These include challenges related to the development of a realistic simulator as well as problems related to the technical side of running a simulator-based training program.

### 3.5.1 Endovascular Simulation

A number of endovascular simulators have been developed over the years that target rehearsal and error reduction through high fidelity computer- and mannequin systems.

The VIST simulator from Mentico has gained popularity in the past 15 years and is now offered by a variety of companies. It has been tested in various carotid stenting and interventional scenarios with varying results. While it is beneficial for novices learning these procedures (Berry et al., 2006; Dayal et al., 2004; Hsu et al., 2004), it does not provide much benefit for experienced interventionalists (Dayal et al., 2004). Results have been mixed regarding its effectiveness in improving procedure time, with some studies showing progress (Patel et al., 2006) and others not (Berry et al., 2006). However, there seems to be consistent improvement in fluoroscopy time (Berry et al., 2006). VIST has also been effective in increasing the amount of contrast injected (Patel et al., 2006). A study by Berry et al. (2006) found that surgeons who used VIST had better visualization of their patients and improved fluoroscopy times during the procedure. All groups in the study had equally rapid learning rates, with a minimum of 12 weeks required to become proficient.

Errors made during procedures can also be affected by simulator use. The ANGIO Mentor simulator, which has advanced haptic feedback mechanisms, has been demonstrated to be effective for psychomotor skill learning in both cardiac stenting and diagnostic cerebral angiography simulation (Alejandro. Spiotta et al., 2011). In this case, residents made more errors in diagnostic cerebral angiography than fellows, although fellows did show improvement on the simulator (Alejandro. Spiotta et al., 2011). In contrast, in a study by Spiotta et al. (2012), residents who practiced on the simulator made fewer errors in cardiac angiography compared to those who only watched videos.

The amount of contrast injected, a substance used to highlight blood vessels during procedures, has also been found to be affected by simulator use, with some studies showing an increase in contrast injection (Patel et al., 2006) and others not finding a significant impact (Lee et al., 2009; a. Spiotta et al., 2011a; a M. Spiotta & Schlenk, 2010).

Virtual angiography simulators, which may be based on real patient data or use computer-generated models, can also be used for training in procedures such as angiography, angioplasty, and stenting. Some examples of virtual angiography simulators include the Endovascular Simulator (EVS) from Surgical Science and the Coronary Angiography Simulator from Anatomage. Using virtual reality systems, computed tomography angiography, magnetic resonance angiography, and 3D imaging can be beneficial for familiarizing trainees with patient anatomy and facilitating surgical planning (Spiotta & Schlenk, 2010).

### 3.5.2 Endovascular Metrics

One of the most widely used metrics to assess performance on an endovascular simulator is the procedural time. This metric provides a bird's eye view of the improvement in the learner's skill through a combined improvement in navigation, tool manipulation, accuracy, motor dexterity and imaging use. Procedural time and fluoroscopy time on simulators is significantly improved in experienced surgeons (Dawson DL et al., 2007; Dayal et al., 2004; Mazzaccaro & Nano, 2012; Patel et al., 2006; Alejandro. Spiotta et al., 2011; Van Herzeele et al., 2008), inexperienced surgeons and junior residents (Aggarwal et al., 2006; Fargen et al., 2012; Klass et al., 2008; Naughton et al., 2011; Willaert et al., 2012) and even untrained students (Coates et al., 2010; Hsu, Younan, et al., 2004; Lee et al., 2009). This significant improvement is seen across all high fidelity simulators, but does not offer the level of skill granularity expected for this procedure and thus is often accompanied by other basic metrics, such as fluoroscopy time, contrast volume and inserted tool time (Dawson DL et al., 2007; Dayal et al., 2004; Mazzaccaro & Nano, 2012; Patel et al., 2006; Alejandro. Spiotta et al., 2011; Van Herzeele et al., 2008; Willaert et al., 2012)(Aggarwal et al., 2006; Fargen et al., 2012; Klass et al., 2008; Naughton et al., 2011)(Coates et al., 2010; Lee et al., 2009).

Studies have gone beyond these metrics to assess events that would potentially create adverse outcomes if performed by inexperienced surgeons or residents. A study by Patel et al., looked at number of catheter handling errors made by cardiologists in simulation, and found a significant reduction with training (Patel et al., 2006). A similar error in tool manipulation – specifically advancement of guidewire without a leading wire – can also be reduced with the help of simulation-based training (Van Herzeele et al., 2008). Overall, simulated endovascular training seems to lessen the number of errors made by novices (Boyle, 2009; Coates et al., 2010).

To assess the use and deployment of tools throughout the procedure, studies have looked at numbers of deployments and the quantity of tools used. Dawson et al. were able to show that simulation-based endovascular training can reduce the number of balloon catheters used, stents implanted and wires inserted (Dawson DL et al., 2007). The placement of the stent during deployment can also be improved with this training (Mazzaccaro & Nano, 2012).

In order to standardize some of the performance scores, a Global Rating Scale has been created and implemented for these procedures. This scale can be beneficial in assessing competencies that have a high translational potential in endovascular aneurysm repair. Using high-fidelity simulators has been shown to improve the GRS scores in experienced surgeons (Fargen et al., 2012, 2013) and novice trainees (Lee et al., 2009).

The role of simulation in providing tailored training which include a wide variety of patient anatomical complexities, pathological presentations and interventional needs cannot be understated. It is vital that training tools are adapted to provide an accurate method of preparing for these factors, and, thankfully, most modern endovascular simulators offer this opportunity. Providing inexperienced surgeons with patient-specific training prior to the procedure can improve their confidence and flow of operation (Willaert et al., 2012), ensuring they are familiar with the anatomy, catheter motions, handling dynamics, tool interactions and techniques (Cates et al., 2007). Using validated simulation-based training modalities to expose inexperienced residents to these operational and situational factors can give them an opportunity to excel in their field and push the boundaries of the standards of care.

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# 4 Integration of Available Tools

This chapter aims to combine Chapters 1-3 to provide an analysis on the gaps that exist within endovascular training and the steps we can take to address them. This section will also outline the purpose of this thesis and the detailed aims which were set out by the research team.

## 4.1 State of Implementation

Implementation of an expensive, high-fidelity simulator into a standardized training program for a minimally-invasive and technically challenging specialty is no simple task. This implementation does not depend solely on the validity of the trainer and the resources available at the training facility. It is a long interplay of successes and relationships between professional societies and medical board examiners, medical schools and teaching hospitals, device manufacturers and regulatory bodies, insurance providers and media coverage, public drive and perception, and its relative importance and need in relation to other specialties, disorders, and crises (Carroll & Messenger, 2008). It is incredibly important to appreciate this complex interplay of factors that can affect the successful implementation of a simulation-based training program.

Models of surgical performance can be used to inform the design of simulation-based training programs in a number of ways. For example, they can be used to predict how often an error will occur (i.e., error prediction), or what kind of error will occur in a given situation (i.e., error identification). They can also be used to provide learning objectives and aids for learning cues (i.e. immediate feedback) and debriefing sessions (i.e., delayed feedback). Currently, much of the simulation-based training is still dependent on availability of guidance and oversight during training. The technology is plentiful and the learners keen to be given the opportunity to tailor their craft, however, we will struggle to catalyze these two factors if our training capacity still hinges on the Master-Apprentice Model and the availability of mentors.

The medical system attempts to have these questions answered, however, it is evident that the capacity is tightening, and the system must adapt to create training opportunities in high efficiency and large availability. Currently, these opportunities are limited by the apprenticeship model, however, many specialties have already started to create environments for trainees to access training tools without supervision, in order to continue developing the competencies at their own pace. Endovascular simulators have the technical capabilities to make this a reality, but too many uncertainties create ambiguities in training potential. What skills should we target during autonomous training? Can we provide meaningful improvement in technical skills without debriefing or immediate feedback? Are there fellows we should prioritize and what standard of performance should we expect on simulated case models?

In the subsequent chapters, we will attempt to explore these questions to provide clarification on the role that simulation can play in interventional radiology. In our first aim, we surveyed neurointerventionalists around Canada to gauge their perspective on the most important steps and the frequency of errors they observe in the Angio Suite. In our second aim, we are going to explore the potential to improve navigational competency through independent, simulation-based angiography training. In our third aim, we focus on the utility of providing anatomy model overlay as a visual assistive cue to facilitate acquisition of technical skills including procedural pace and navigation. In our final aim, we will explore the ability of fellows to learn and improve aneurysm coiling metrics using self-guided training curricula.

# 5 Aim 1 - Perceived Significance of Clinical Steps and Frequency of Errors in Cerebral Aneurysm Coiling

## 5.1 Contributors' Statements

OZ was responsible for participant recruitment, data collection and interpretation, data visualization, and manuscript preparation. MB revised data collection tools, interpretation of collected data and questionnaire content. RE revised data collection tools, assisted in interpretation of collected data, and revised the manuscript draft. SR designed data collection tools, monitored the data collection progress, and revised the manuscript draft. All members of this study had a strong role in study design.

## 5.2 Abstract

Cerebral aneurysm coiling is a technically challenging endovascular procedure demanding substantial hands-on clinical experience. As part of the compulsory angiography training, junior fellows learn and develop a repertoire of complex mechanical skills within the boundaries of the operating theatre (Angio Suite), guided by expert interventionalists. Assessment of clinical fellowship completion relies on operating experience and subjective assessments used by senior specialists, lacking the formalized use of tested objective performance criteria often seen in other medical specialties. In order to advance training in this field, objective methods of assessments need to be created, validated and applied to available training systems. This assessment seeks insight into the uniformity of clinical practice and the accuracy of expected relationships between procedural steps.

A multiple-phase Delphi assessment was distributed via SurveyMonkey to the Canadian Interventional Neuro Group (CING). A total of 85 practicing expert interventionalists across Canada were queried on their perception of the importance, frequency and severity of core steps and errors in cerebral angiography and aneurysm coiling.

A total of 21 expert responses were obtained. The most important steps pertained to the aneurysm coiling stage, with the most disagreement revolving around techniques in femoral artery puncture and catheterization of the aorta. The highest frequency of errors was reported

during the advancement of gauge and starter wire at the start of the procedure. Highest scores of error severity were seen in microcatheter advancement and coil deployment within the aneurysm.

These results identify areas of training that are exposed to the highest level of risk (e.g. steps within the aneurysm coiling stage) or highest rate of error (e.g. aortic and supra-aortic catheterization) which can be used to create focused training modules. More subtle errors, such as tool exchanges and flushing maneuvers, would greatly benefit from being integrated further into simulation-based training.

## 5.3 Introduction

The clinical and educational scopes of surgery have undergone significant changes over the past two decades, which have created opportunities to improve medical training, but have also introduced significant challenges. As long as surgical education continues existing under largely apprenticeship-style training programs, there are always going to be interpersonal differences in techniques, scope and performance (Armstrong & Barsion, 2013; Evans et al., 2016; Lucey, 2013). And yet, clinical outcomes continue to edge closer to excellence with every cohort.

Cerebral angiography is largely considered to be a safe, minimally invasive procedure, which sees a modest 3-5% neurological complication rate (Kaufmann et al., 2007) The maintenance of these rates in new cohorts is largely dependent on the education that is provided by the attending neurosurgeon (Ludmerer, 2004). Although the universally accepted standard of clinical competency still revolves around case exposure totals, advanced training methodologies, such as the use of simulation, are being introduced (Gordon & Buckley, 2009; Kahol et al., 2010; Kneebone, 2009; Stefanidis, 2010; Watters & Truskett, 2013; Ziv et al., 2005).

Simulation-based training can offer an incredible opportunity to hone the skills and techniques necessary for expert performance, however, it requires the methodologies to be honed as well. Assessments of complementary simulation-based training tend to fall on most accessible and obvious metrics to provide broad training scopes, rather than pin-pointed skill development for which they were intended. The primary link is foremost not whether the techniques trained on simulators could be reproduced in a clinical environment, but rather whether they reflect the training scope and emphases made by the attending surgeons in that very same environment.

Understanding the perceptions of the importance, frequency and risk of key steps by experts in cerebral angiography would provide an informed insight into the specific subsets of skills being focused on in the clinical space, and the skills more suited for training in complementary settings, such as simulation labs. With the increasing availability of new tools and techniques, it's an on-going struggle to use all available training tools effectively (Borkett-Jones & Morris, 2010; Brydges et al., 2009; Gaba, 2007; Hughes et al., 2013). As we strive to follow the 'practice makes perfect' idiom, the complexity of this field continues to indicate that practice only makes 'permanent' and only perfect practice makes perfect.

Creation of perfect practice requires an in-depth understanding of the combination of skills that create the most competent neurointerventionalists. Therefore, the experts must be integral to the on-going refinement process of the training process, in the surgical suite and the simulation lab. To connect the two environments, we set out to better understand the current state of the clinical environment – the significance of procedural milestones, potential risks involved and their incidence – to be able to proactively connect it to the increasing complementary simulation-based training.

## 5.4 Methods

### 5.4.1 Study Format

A detailed survey was distributed via SurveyMonkey to the Canadian Interventional Neuro Group (CING). A total of 85 practicing expert interventionalists across Canada were queried on their perception of the importance, frequency and severity of core steps and errors in cerebral angiography and aneurysm coiling. Participants were provided with opportunities to provide feedback on the accuracy of the steps outlined. Questions containing feedback or discrepancy in outcomes were reformatted and resubmitted to active participants until an agreement was reached.

### 5.4.2 Survey Content

Participants were asked to grade the importance (not at all important, slightly important, somewhat important, very important, and extremely important) of steps within broad procedural categories (patient preparation and setup, femoral artery puncture, catheterization of the aorta, catheterization of supra-selective blood vessels, aneurysm coiling, task completion and overall procedure). Participants were subsequently asked to grade the frequency (not often at all, occasionally, sometimes, frequent, or always) and severity (unimportant, minor, moderate, severe, or life threatening) of errors pertaining to the steps within these categories. Finally, the participants were asked to rank the order of importance, frequency and severity queries. The survey also contained decoy questions, a set of simple questions with easily identifiable answers, in order to gauge the experts participation validity.

### 5.4.3 Data Analysis

Data was exported from SurveyMonkey and processed in Excel. Data points were blocked by theme and aggregated into question categories. Comments were extracted and reframed as questions for subsequent surveys. Data analysis and visualization was completed using Tableau Public.

## 5.5 Results

Out of the 85 experts contacted within the CING, 21 (M:F 16:5, mean age 48.4 years) had agreed to participate in the first round of the survey. The first-round cohort was almost entirely Canadian-practicing (Canada: n=20, USA: n=1) neurosurgeons (n=8) and neuroradiologists (n=13), all of whom are trained to and currently perform cerebral aneurysm coiling procedures. Four of the participants did not have a currently active teaching responsibility, with 16 currently involved with teaching cerebral angiography, and 14 currently involved with teaching cerebral aneurysm coiling. Eight experts had participated in the revised round of the survey, after which a consensus was reached, evidenced by a lack of novel objections to the question content.

### 5.5.1 Importance of Clinical Steps

When assessing the importance of steps, most experts rated a large subset of actions as either very important or extremely important. The exception to this are the steps that had disproportionate number of low importance ratings, such as incising parallel to the inguinal crease (Q12d), performing a single-wall puncture (Q12f), following with catheter using fluoro (Q14d), flushing of catheter (Q14e, Q15c) and using a closure device (Q17b) (Figure 9**).**

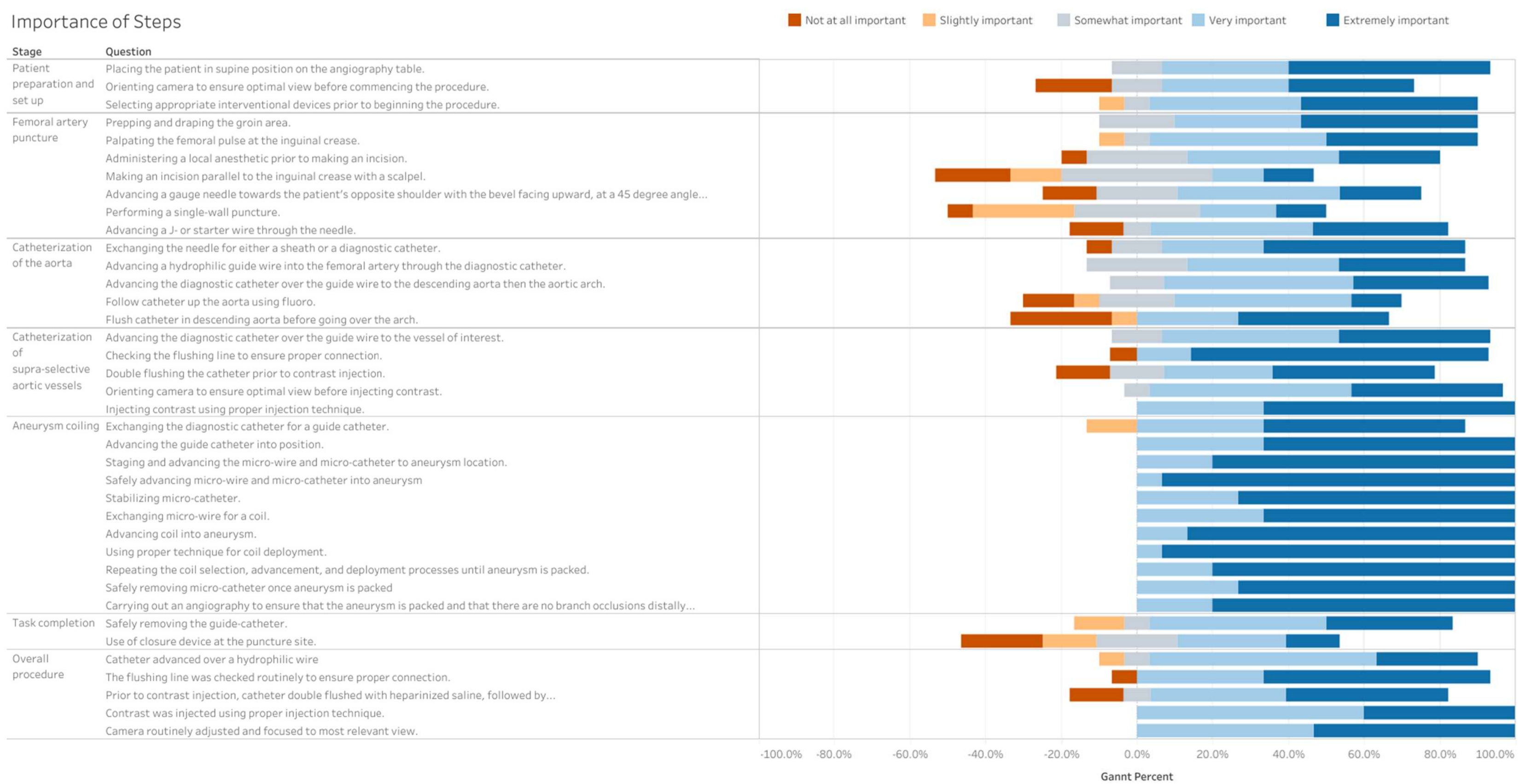



**Figure 9 - Perceived importance of clinical steps**
**The importance of clinical steps within specific stages of a cerebral angiography procedure, as rated by expert neurointerventionalists.**

Comments provided by experts clarified the reasoning for the lowered importance scores of some steps (Table 1).

**Table 1 - Comments provided by experts that pertained to steps that had more disagreement between the participants**

| Question | Comments |
|---|---|
| incising parallel to the inguinal crease (Q12d) | • Inguinal crease is not a satisfactory landmark for femoral puncture<br>• Use of ultrasound guidance |
| flushing of catheter (Q15c) | • Double flushing is important each time the wire comes out if not using a continuous flush<br>• aspiration of the catheter before injection is extremely important. I do not use flushing line for diagnosis angiography |
| using a closure device (Q17b) | • A closer device may or may not be used. The sheath can be removed with manual pressure<br>• Closure device versus manual compression would have made more sense |

### 5.5.2 Frequency of Errors

When grading the frequency of errors made during the clinical stages, experts tended to agree on generally higher rates during femoral artery punctures, catheterization of vessels, and overall procedural tasks (Figure 10). Comments provided by experts to clarify their scoring can be seen in Table 2.

**Table 2 - Comments provided by experts that pertained to steps that had more disagreement between the participants**

| Question | Comments |
|---|---|
| incising parallel to the inguinal crease (Q22d) | • The use of ultrasound guidance has drastically reduced these events.<br>• need to know how to puncture with sonography if unable to identify the femoral pulse |
| flushing of catheter (Q23) | • I use a continuous forward flush system and never flush the catheter in the descending aorta |
| using a closure device (Q27) | • We often use manual compression versus closure device |

### 5.5.3 Severity of Errors

When assessing the severity of potential errors, the experts tended to agree that errors during patient preparation and femoral puncture had less severity, especially compared to the moderate severity of errors made when catheterizing vessels, and high severity of potential errors made during aneurysm coiling (Figure 11).


**Figure 10 - Perceived frequency of clinical errors**
**The frequency of clinical errors within specific stages of a cerebral angiography procedure, as rated by expert neurointerventionalists.**

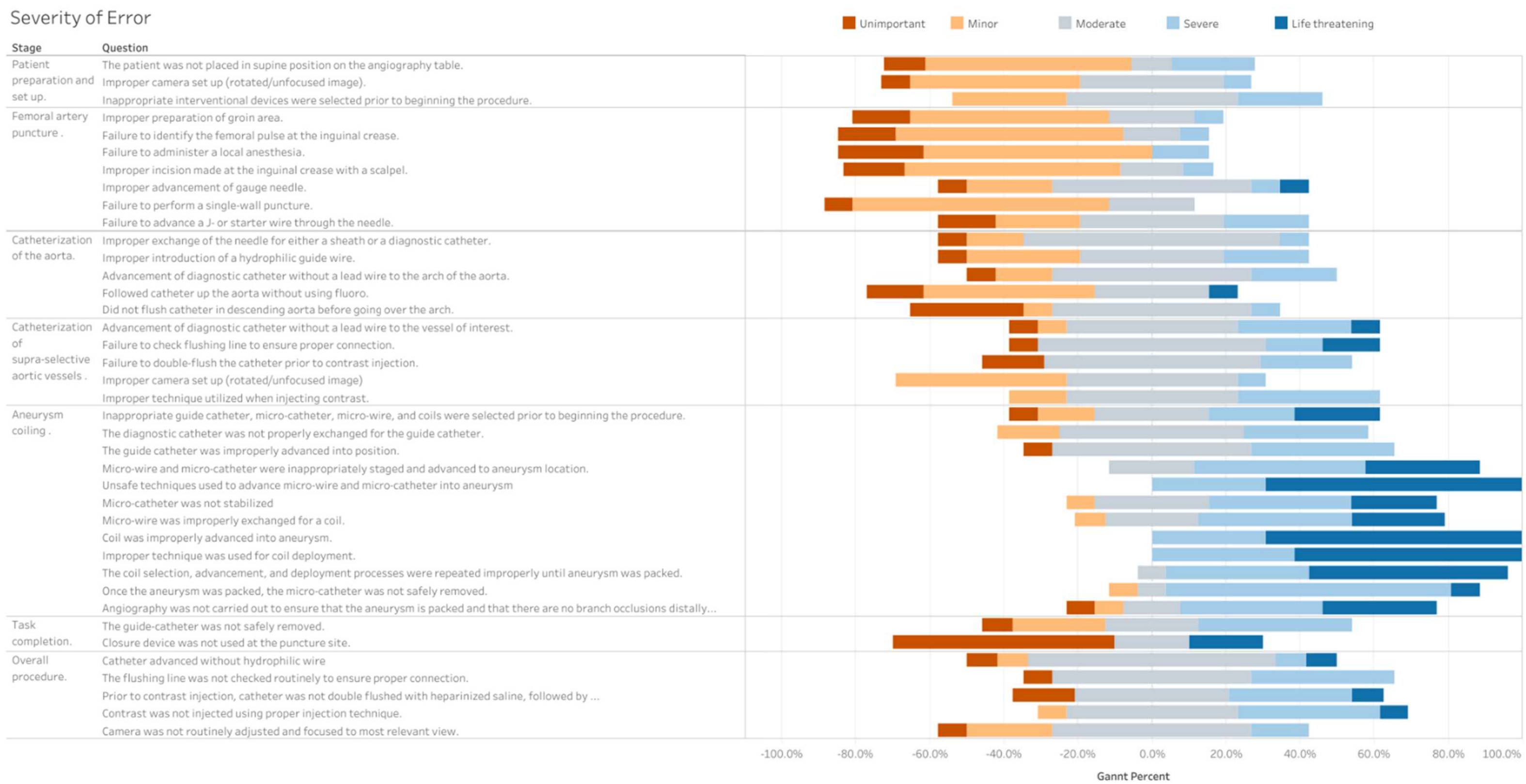
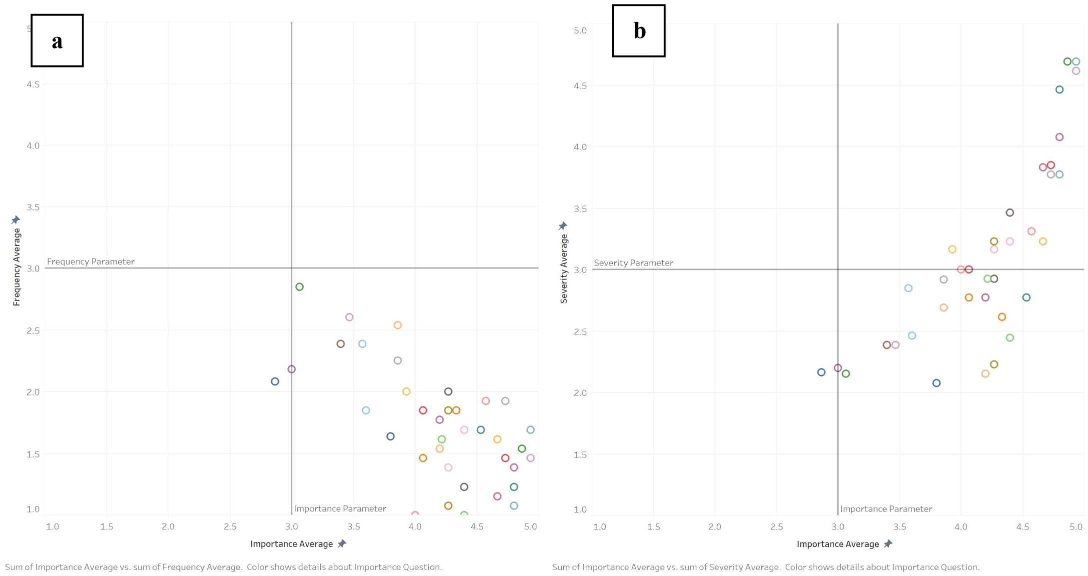



**Figure 11 – Perceived severity of clinical errors**
**The severity of clinical errors within specific stages of a cerebral angiography procedure, as rated by expert neurointerventionalists.**

### 5.5.4 Paired Analysis of Significant Events

Distribution of answers along different scoring criteria as comparative axes provided a correlation visual (Figure 12). Assessing the relationship between importance of and error frequency within specific clinical stages revealed that steps which are generally deemed less important tend to see higher rates of errors (a). The comparison of importance of steps and severity of errors within them revealed a positive correlation – steps which are deemed most important, such as appropriate vessel catheterization and aneurysm coiling, would generally have much more severe consequences if they were not performed correctly (b). Lastly, a comparison between frequency and severity of errors within each clinical stage revealed that steps with the highest possible error severity, such as aneurysm coiling, were much less frequent (c).



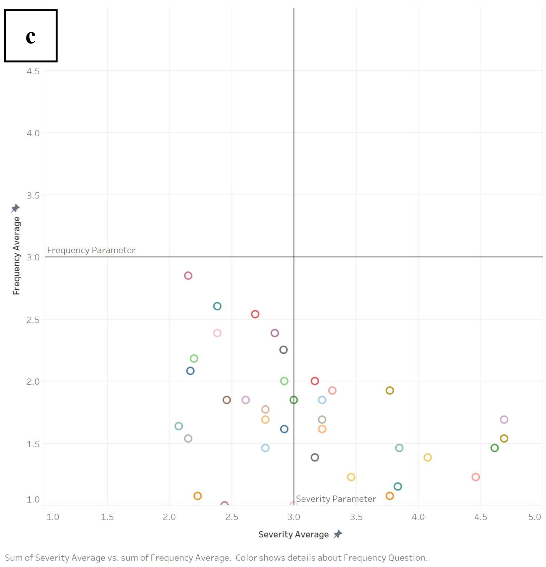




**Figure 12 – Step importance, error frequency and severity compared**

**Paired distributions of the perceived importance of steps and error frequency (a), perceived importance of steps and error severity (b), and perceived error frequency compared to their perceived severity (c).**

### 5.5.5 Decoy Questions

The decoy questions were answered fully by all participants with 100% agreement. The true-or-false questions – such as “Groin assessment is unnecessary if a closure device is employed.” and “A large gauge access guide catheter in addition to a diagnostic catheter is helpful for routine angiography.” – identified that experts completing the survey were critically assessing the questions posed in the survey.

## 5.6 Discussion

As we start relying more on simulation-based training we can easily fall into the traps of measuring success based on simulated performance and basic metrics, such as procedural time (Jensen et al., 2016; Klass et al., 2008), fluoroscopy use and contrast injections (Glaiberman et al., 2008; Spiotta et al., 2011). The promise of these studies advocates for the implementation of simulation into training curricula (Kreiser et al., 2021), however, these factors present just the tip of the iceberg that is the combined skillset of an efficient, expert neurointerventionalist. In fact, due to the multi-dimensional skillset required for optimal performance, many recommend that simulation-based training is provided with adequate supervision (Pannell et al., 2016), an ask that is hard to meet with the already limited hours available.

### 5.6.1 Ratings of Clinical Step Importance

Since the steps that were listed in the survey all played a key required role in cerebral angiography procedures, the only steps that were rated lower, such as incision location, catheter flushing and closure protocols, are those that had varying availability and standards of those devices in the clinical environments were the participants practice. This can be a useful way to identify how individual practices differ across the country as a variety of techniques are employed.

### 5.6.2 Ratings of Error Frequency

The findings in this study identify an important metric that can often be missed by patient outcome statistics – the perception of events by attending surgeons that include or lead to improper use of tools and techniques. The survey identified key clinical steps where mistakes took place more frequently – such as during tool exchange and associated flushing maneuvers, and tool movement. These subtle errors are harder to measure and identify using metric-based simulator assessments that tend to hyperfocus on easily measurable data and dimmish the representation of error outcomes.

### 5.6.3 Ratings of Error Severity

Aneurysm coiling is the most complex and nuanced skillset within this procedure which carries heavy implications for any errors that are made during this stage. It is not surprising that the clinical and simulated environments both put a very high emphasis on ensuring that this stage of the procedure sees the lowest rates of errors. However, this mountain of expectations casts a large shadow over the underlying skillsets that may go underdeveloped, and may be quickly resolved either through mentored training workshops or self-guided task training modules.

### 5.6.4 Paired Comparisons

Direct paired comparisons between importance, frequency and severity results provides a guideline for the strategic assurance of competency after training. The clinical steps which yielded the highest frequency of low-severity errors are potential candidates for standardized metrics implementation in order to create performance benchmarks as qualifying assessments of competency, as these are likely to be overshadowed by high-severity risk steps during clinical training. Skills which are key to preventing the low-frequency, high-severity errors are targets for focused, mentored practice using de-risking training strategies, such as technical simulator trainers and case-based analyses. The clinical steps which do not yield a significant frequency or severity of errors can be deprioritized in complementary training to reallocate finite training resources to the development of other skills. Bringing these findings into a comprehensive program could significantly improve the efficacy of medical training by providing clarity and evidence for perfect practice.

## 5.7 Conclusions

The results of this survey indicate that neurointerventionalists generally agree on the importance, frequency, and severity of clinical errors in cerebral aneurysm coiling procedures. Most experts rated a large subset of actions as either very important or extremely important, with the exception of a few steps that were rated as less important. Experts also tended to agree on the general frequency and severity of errors made during different stages of the procedure. A paired comparison of the answers provided by the experts suggested a relationship between the importance of clinical steps and the frequency of errors, as well as between the frequency of errors and their severity. Overall, these results suggest that neurointerventionalists are in agreement on the key factors related to clinical errors in cerebral aneurysm coiling procedures.

In the future, it may be useful to conduct additional research to identify the reasons for these discrepancies and to explore potential strategies for reducing the occurrence of clinical errors in cerebral aneurysm coiling procedures. This could include the development of new training programs, the use of new technologies or techniques, or the implementation of guidelines or protocols to improve patient safety. Additionally, further research could be conducted to assess the effectiveness of these strategies and to determine how they impact the incidence of clinical errors in this field.

The success of medical and surgical training programs around the world is often measured by the competency of their graduates. A modern multi-dimensional training curriculum is the cornerstone to that success, and can only be ensured through a methodical application of training modalities' strengths, such as task repetition. As we continue to develop more sophisticated and more competent complementary simulation systems to provide us with the answers, we should continue to reflect within the clinical environment to ensure we are asking the right questions.

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# 6 Aim 2 - Assessment of Novice Navigational Skills in Simulated Cerebral Angiography

## 6.1 Contributors' Statements

OZ was responsible for participant recruitment, data collection and interpretation, data visualization, and manuscript preparation. MB revised data collection tools, interpretation of collected data and revised manuscript draft. RE revised data collection tools, assisted in interpretation of collected data, and revised the manuscript draft. SR designed data collection tools, monitored the data collection progress, and revised the manuscript draft. All members of this study had a strong role in study design.

## 6.2 Introduction

Integration of simulation-based medical education (SBME) into traditional training approaches has the potential to drastically improve the rate of clinical skill acquisition and reduce overall strain on the medical system. One of the arguable strengths of SBME lies in creating a safe environment for trainees to make and learn from mistakes that would otherwise have been harmful for patients (Ziv et al., 2005). This is especially significant in skillsets consisting of steep learning curves, such as those found in cerebral angiography (CA) training.

Development of endovascular proficiency in CA requires multimodal acuity due to the limited visuospatial feedback – a distal guidewire tip is hard to navigate through the lumen of 3-dimensional vascular anatomy using temporally-constrained 2-dimensional fluoroscopic imaging. These motor and visuospatial skills comprise the core of CA and should ideally be trained extensively outside of the hybrid operating room (Angio Suite). Unfortunately, current angiography fellowship programs still rely on traditional Angio-Suite-based training methods for skill development despite the availability of haptic simulators.

One of the most established high-fidelity simulators available is the ANGIO Mentor from Simbionix. This task-trainer has been shown to have construct validity (Nguyen, Eagleson, et al., 2014), improve psychomotor learning (Alejandro. Spiotta et al., 2011), reduce procedure and fluoroscopy time (Lee et al., 2009; Alejandro. Spiotta et al., 2011; Zaika et al., 2016), and enhance resident performance (Seymour et al., 2002). Although impressive, this has not led to a widespread adaptation of simulation in angiography training. Introduction of SBME is generally limited by scarcity of human resources, logistical barriers and laborious coordination (Stefanidis et al., 2015), however, its particularly lagging implementation in CA may be attributed to insufficient identification and standardization of targetable skills.

Recognizing training obstacles for novice trainees is a key component in tailoring their learning experience and providing standardized goals. Some of the most basic errors committed by novices are purely navigational – limited imaging, inexperience and excessive tool manipulation (Dayal et al., 2004; Patel et al., 2006) can cause major errors (Coates et al., 2010) and deviations from their expected trajectory (Figure 13). However, most proficiency assessments still focus on subjective grading schemas and program-based case exposure requirements.

The literature does not currently explain how junior trainees develop navigational competence, despite its necessity for expert performance. This level of granularity in skill development has been difficult to measure in the Angio Suite due to the multifaceted operational components of the procedure, such as fluoroscopy time and contrast use. Spatial ability may play an important role as it has been shown to be correlated with greater performance across a variety of specialties including laparoscopy (Keehner et al., 2004), colonoscopy (Luursema et al., 2010) and sonography (Clem et al., 2013), but is not used in determining training needs.

Creating opportunities for trainees to rehearse and make navigational errors in simulation, even without expert guidance, may lead to an overall reduction in their prevalence. We aim to understand the prevalent navigational errors in simulated CA and their potential for correction through a structured, self-guided simulation training program. By established guidelines for this metric, it may be possible to decrease simulation adoption barriers by reducing physician mentoring stress and encouraging self-regulated practice.

## 6.3 Methods

The purpose of this study was to identify improvement in navigational errors in self-guided cerebral angiography simulation training in novices.

### 6.3.1 Equipment

A haptic feedback simulator, ANGIO Mentor by Simbionix (Figure 14), was used to train, test and collect data from the participants. Trainees were instructed on basic functionality of the control panel, including rotating fluoroscopy C-arm, shifting patient table, creating and clearing roadmaps, injecting contrast, activating fluoroscopy and performing a digitally subtracted angiogram of the aneurysm. Two monitors were used to display the tool and patient state (b) and patient fluoroscopy imaging (c).

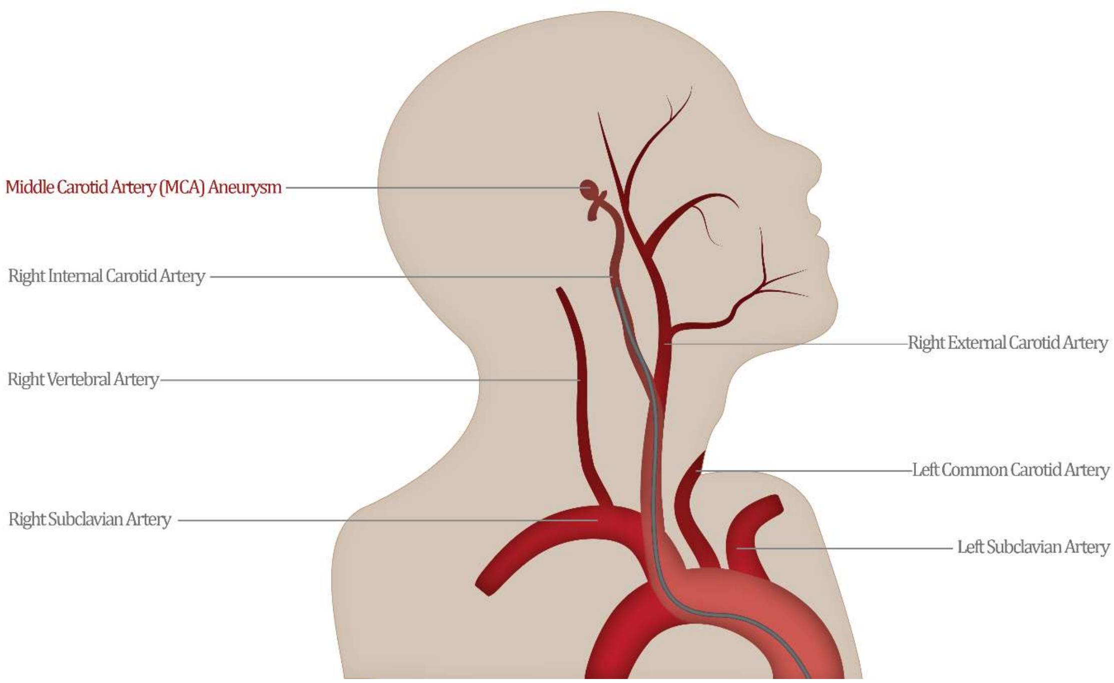



**Figure 13 – Correct path to R-MCA aneurysm site**

**An expert interventionalist would establish the most direct path to the site of the aneurysm (highlighted), avoiding any deviations and bifurcations that would lead to lost procedural efficiency (red).**

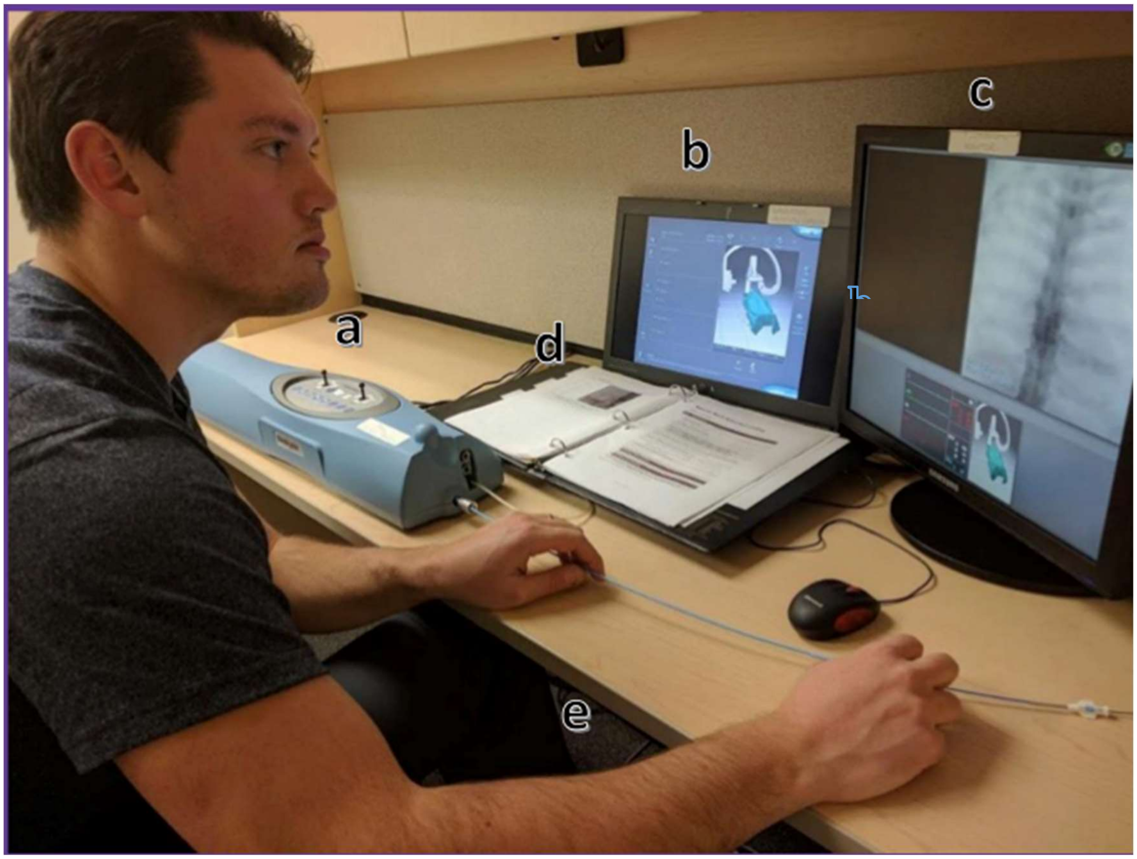



**Figure 14 – ANGIO Mentor simulator**
**The ANGIO Mentor by Simbionix includes a simulation control panel (a), main tool interface (b), fluoroscopy screen (c), instructional booklet (d) and pedals (e).**

### 6.3.2 Study Design

A total of 8 Clinical Anatomy graduate students and 6 residents in neurosurgery and radiology specialties were recruited for this study. The cohort was selected due to their unique combination of vascular anatomy competency and lack of technical endovascular training. Although this combination provided a uniform baseline of experience, it limited the number of participants available to be recruited. Participants were provided with a neurovascular overview, followed by a vascular anatomy labelling quiz. A grade cut-off of 80% was used to remain in the study.

Participants attended 8 sessions which consisted of an untimed unique practice case (left internal carotid artery (L-ICA) aneurysm) to familiarize participant with the equipment, and a timed test case (right middle cerebral artery (R-MCA) aneurysm) with a step-wise instructional sheet. Session quantity was chosen to ensure a significant time frame for learning to occur. Participants were allowed to ask questions during practice, but had no assistance in the test case until the case was finished. A case was deemed to be finished when the participant declared that they have achieved the last step in their instructions.

### 6.3.3 Outcomes

In assessing the capacity of navigational skills, several quantitative performance attributes were extracted from the simulation software. Using the participant performance log files, the locations of the tools throughout the procedures were used to calculate frequency and length of vessel access. Navigational errors, or access of incorrect vessels along the optimal vascular trajectory, were assessed using these markers. Time spent exploring incorrect vessels is likely to increase total fluoroscopy time and negatively impact patient outcomes (Willinsky et al., 2003).

### 6.3.4 Error Criteria

The correct pathway for navigating to an R-MCA aneurysm included the most direct endovascular trajectory, a route that is used clinically for accessing aneurysms on the right side of the brain – arch of the aorta, brachiocephalic (ie. R-SUB), right common carotid (R-CCA) and internal carotid arteries (R-ICA). A navigational error was deemed to be any deviation from this pathway into a neighbouring artery. Thus accessing the following areas with either the guidewire or the catheter was included as a navigational error – left subclavian (L-SUB), left common carotid (L-CCA), right vertebral (R-VERT) or right external carotid (R-ECA) arteries.

### 6.3.5 Spatial Ability Groups

Participants were given two consecutive Vandenberg and Kuse (Vandenberg & Kuse, 2011) Mental Rotation tests (MRT) to assess visual-spatial skills. Each test contained 12 questions and was timed at 3 minutes. The scores were used to split participants post hoc into a low MRT group (score less than median) and high MRT group (score higher than median). There is evidence to suggest that comparing lower and upper quartiles may be more appropriate to contrast the scores (Wanzel et al., 2002), however, this was not possible in our sample size. MRT groups were compared to each other with respect to time spent in incorrect vessels.

### 6.3.6 Chance Design

The difficulty of entering one of the great vessels was assessed through chance. The guidewire was inserted blindly into the simulated patient and advanced the distance of the arch of the aorta. The resulting location of the guidewire was recorded. The tool was advanced for 50 cycles without guidewire rotation and for 50 cycles with a clockwise rotation per inch of insertion.

### 6.3.7 Data Collection

All data was automatically collected by the simulator and analyzed manually using Microsoft Excel. Vessel access timestamps were analyzed for frequency and compiled together to calculate duration of stay within each vessel.

### 6.3.8 Statistical Analysis

The simulator data was exported and analyzed using Excel and SPSS 19. Timing and frequency of vessel access across 8 sessions was analyzed using a repeated-measures independent analyses of variance (ANOVA) with a Bonferroni correction. MRT influence was also assessed using a two-way repeated measures ANOVA. A statistical significance of $p<0.05$ was used for all assessments.

## 6.4 Results

All participants passed the anatomy labelling quiz by scoring 80% or above, and completed the entire testing protocol.

### 6.4.1 Time Spent in Incorrect Vessels

All participants had significantly improved performance over 8 sessions by reducing their time spent in incorrect vessels ($p<0.05$) while navigating through a diagnostic R-MCA cerebral angiography case with both guidewire and catheter (Figure 15). The average time spent in incorrect vessels with the guidewire dropped from 153 seconds to 44 seconds using the catheter and from 117 seconds to 44 seconds using the guidewire (Figure 15). Comparing this result with our previous study assessing total procedural times (Zaika et al., 2016), it is indicative that one of the main reasons users improve their procedural time is their lowered time wasted on navigational mistakes.

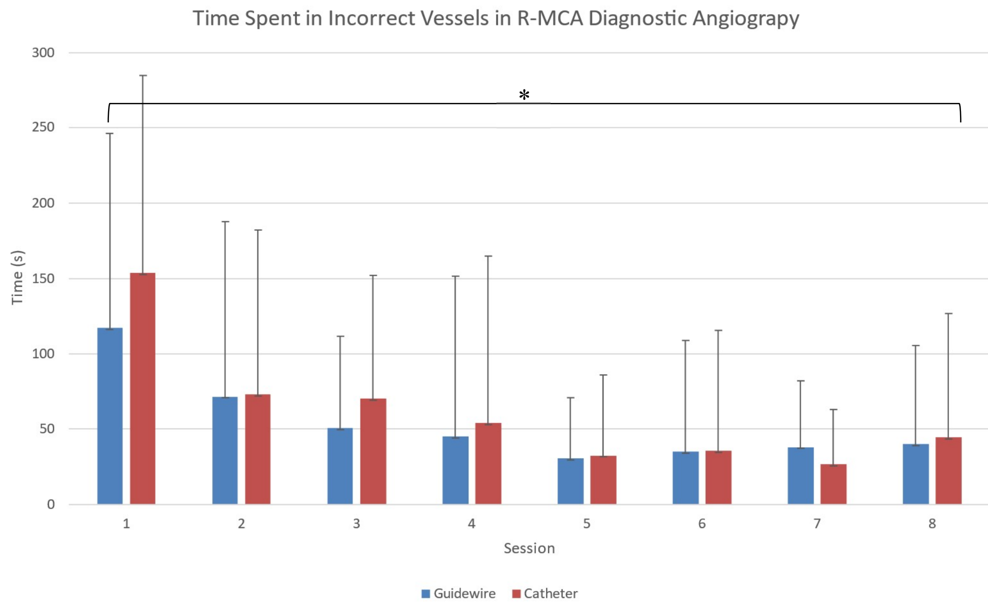



**Figure 15 – Novice navigation through all incorrect vessels**
**All participants had significantly lowered time spent in incorrect vessels with both catheter and guidewire from session 1 to session 8 (*p<0.05)**

### 6.4.2 Vessel Access Time

When analyzed by vessel, time spent in each vessel differed greatly. Based on the participants first session performance, accidentally entering the R-ECA resulted in the highest amount of time wasted, compared to lower duration in L-CCA, L-SUB, and R-VERT. The participants spent a total of 362 seconds (22%) in the L-SUB artery, 281 seconds (17%) in the L-CCA artery, 65 seconds (4%) in the R-VERT artery and 931 seconds (57%) in the R-ECA artery **(**Figure 16**)**. By session 8, participants were spending a total of 35 seconds (6%) in the L-SUB artery, 15 seconds (3%) in the L-CCA, no time in the R-VERT artery and 509 seconds (91%) in the R-ECA. There was an observed reduction in all erroneous vessels access, however, the ratio of errors increased in the R-ECA, indicating that this navigational and spatial issue is not as easily resolved with general practice. The concern is two-fold in that this particular mistake could cause the most damage due to the small lumen of the R-ECA. The frequency of navigational errors may not be the dominant concern, since how those errors are corrected seems to have a larger effect on performance: a novice that spends more time readjusting within the R-ECA may be in need of more training than their frequency-matching colleague.

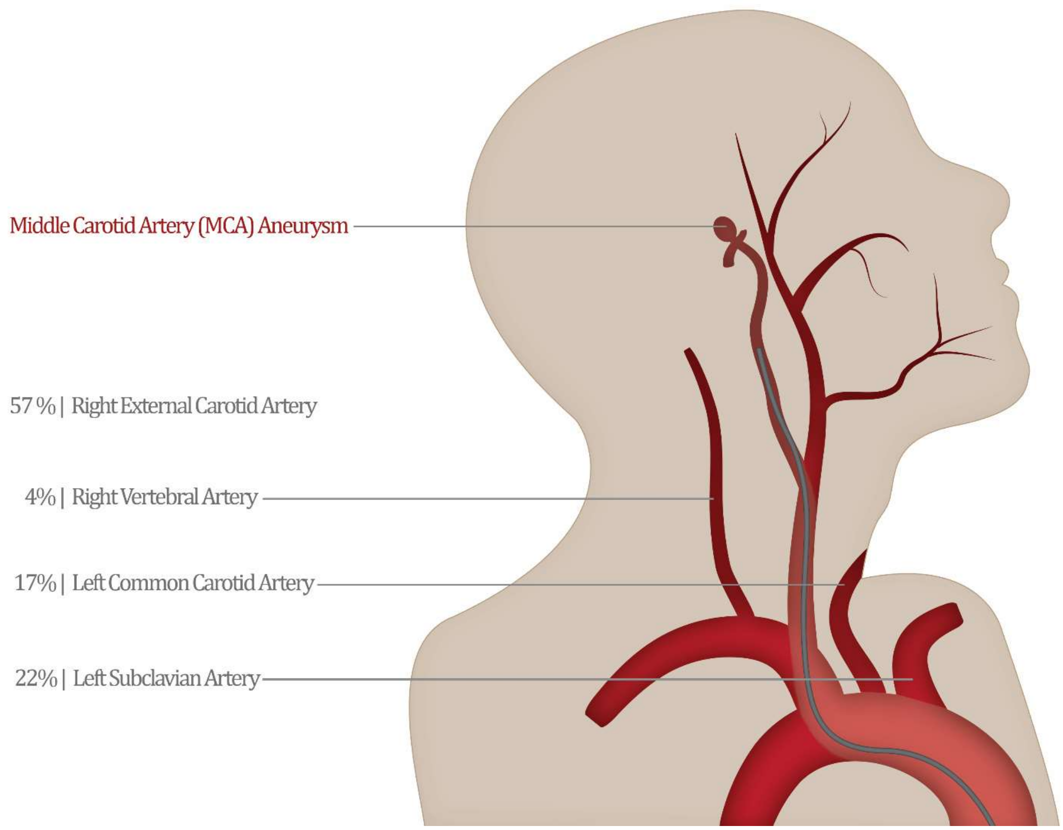



**Figure 16 – Novice navigation time through each incorrect vessel**
**Time spent in each incorrect vessel differed drastically from its access frequency, with the R-ECA requiring the most time of all mistakes.**

### 6.4.3 Frequency of Incorrect Vessel Access

The frequency of incorrect vessel access varied tremendously based on the anatomical area. The alternate pathways off the arch of the aorta saw the highest frequency of erroneous access, with the left subclavian artery and left common carotid arteries being entered with guidewire on average 2.1 and 1.8 times in the first session. The R-VERT access time was insignificant (0.1 times) and its position relative to the trajectory of the guidewire would not be considered a navigational obstacle. The access to the R-ECA, although accessed only 0.9 times on average in the first session, presents a large issue for training professionals (Figure 17).

By the last session, the participants were on average accessing most erroneous vessels with a lower frequency; the L-SUB 0.5 times, the L-CCA 0.6 times, R-VERT 0.2 times, and R-ECA 0.2 times. The L-SUB, L-CCA, and R-ECA had a statistically lower access rate ($p<0.05$), whereas R-VERT did not have a significant change.

The drop in access frequency for some of the incorrect vessels, such as L-CCA and L-SUB, points to the concept that trainees are developing a better understanding of the spatial trajectory and can make corrections throughout training. Unchanged levels in right vertebral artery access confirm this is not a major obstacle in accessing the R-ICA. The major issue seemed to arise from accessing the R-ECA whilst attempting to traverse into the R-ICA. Over the 8 sessions, there was no significant decrease in R-ECA access frequency. This result identifies that either (a) this error cannot be fixed with just 8 training sessions or (b) this error needs to be addressed in a targeted manner. The anatomy of the anterior-posterior overlap between the external and internal carotids suggests that trainees may need further training to better formulate the spatial relationship in their fluoroscopy interpretation.

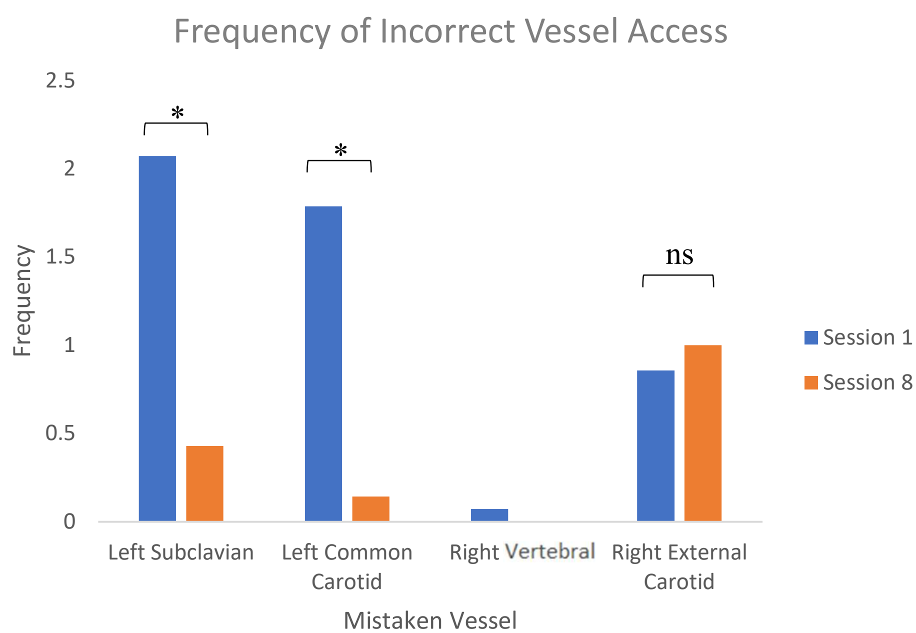



**Figure 17 – Novice access frequency of incorrect vessels**

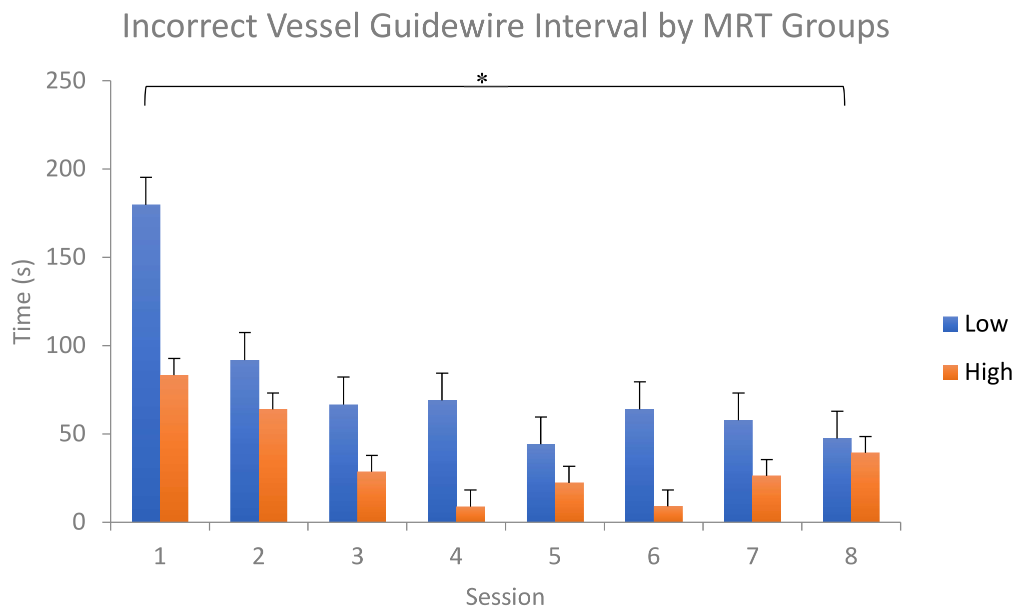
**Frequency of accessing the L-SUB and L-CCA dropped significantly (*p<0.05) from session 1 to session 8, however, this change was not observed in the R-ECA access frequency.**

### 6.4.4 Chance of Access

Upon insertion, the guidewire and catheter were consistently simulated facing in the medial direction. A blind insertion of guidewire into the system over 50 cycles showed no accidental access into the L-CCA or L-SUB, with all trajectories ending up at the base of the aorta. Once a steady rotation was applied over 50 cycles, the guidewire accessed the left subclavian artery 21 times (42%) and only finished at the base of the aorta 29 times (48%). This data could explain why even high spatial performers make the mistake of accessing the wrong great vessels at the start of the procedure. As they advance their tools and rotate them, their chance of accessing the wrong vessel increases considerably. Novices tend to use too many movements while performing the procedure (Antoniou et al., 2011), and may benefit from simulated practice on smoother rotations and motions using endovascular tools.

### 6.4.5 Spatial Ability Groups

There were 7 participants per group, with the low MRT group (MRT ≤ 13) averaging 9.21 and the high MRT group (MRT ≥ 14) averaging 15.86. Individuals with low MRT score spent significantly more time ($p<0.05$) in the incorrect vessels than those with high MRT score, shown with both the catheter and guidewire timing. In our analysis of MRT groups, the results were quite consistent with previous research (Zaika et al., 2016).



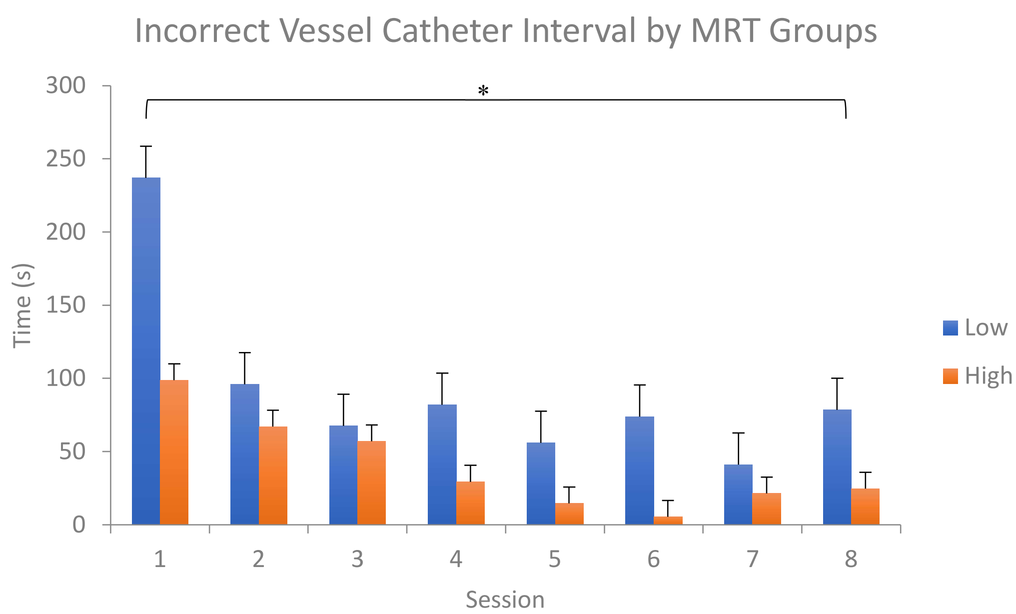




**Figure 18 – Incorrect Vessel Use by MRT Groups**

**Participants with a low MRT score spent significantly more time exploring incorrect vessels with the guidewire and catheter, compared to the high MRT participants (*p<0.05).**

## 6.5 Discussion

In the field of cerebral angiography, simulation training has already been shown to drastically reduce fluoroscopy and procedural time in novice trainees (Lee et al., 2009; Alejandro. Spiotta et al., 2011; Zaika et al., 2016). Although useful in assessing overall performance, these metrics don't provide insight into how and why the trainees improve, dismissing the incredible capacity to target specific skills using SBME. This data identifies simulation's potential in being used to gain vascular familiarity, navigate endovascular tools, and interpret fluoroscopic images. Just as importantly, although interventional fellow training in simulation offers no direct benefit to the patient (compared to training in the Angio Suite), training basic skills independently may significantly reduce physician mentoring stress and reallocate expert interventionalist time back to the patient. By alleviating some of these implementation barriers, complementary simulation training can make skill acquisition much more affordable, accessible, manageable and measurable.

Although the improvement in navigational skills in simulation is encouraging, it should be recognized that this study was focused on simulation-only training and testing. The translation of skills learned in simulation into the Angio Suite would be the true test of its potential and would be necessary to create an adoptable training curriculum. In its development, the training module would greatly benefit from increased focus on the problematic vessels, such as the external carotid artery, in order to standardize performance across the entire endovascular pathway. Additional resources and continued education can be provided to fellows who find the procedure challenging (i.e. low MRT individuals).

As specialties continue to turn to personalized and supplementary training curricula, a paradigm already seeking momentum in medicine (Brunner et al., 2004), there will be an increased need for unsupervised, self-guided simulation practice. The evolution of medical education towards a competency-based learning model will require standardized performance markers established through a strong collaboration between researchers, expert interventionalists and medical educators. This approach to training would enable data-driven analyses of performance to reveal new markers of performance essential for improved patient safety. Furthermore, medical educators can create personalized approaches to target common errors committed by interventional fellows as well as challenging vascular variations. As this research progresses, navigational schemas for vessel difficulty would create a strong personalized curriculum adaptable to the deliberate training needs of the fellow and the outcome needs of the patient.

## 6.6 Conclusion

Simulation-based angiography training is the key to establishing standardized training requirements to target core skillsets in junior fellows. Trainees should be able to learn the essential navigational and motor skills independently using simulation and transfer those skills to a clinical setting under expert guidance. By identifying areas of navigational difficulty, the limited training resources can be better allocated towards focused needs of interventionalists.

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# 7 Aim 3 - Visuospatial Assistance in Simulation-based Cerebral Angiography Training

## 7.1 Contributors' Statements

OZ was responsible for participant recruitment, data collection and interpretation, statistical analysis, figure illustrations, and manuscript preparation. RE revised data collection tools, assisted in interpretation of collected data, and revised the manuscript draft. SR designed data collection tools, monitored the data collection progress, and revised the manuscript draft. All members of this study had a strong role in study design.

## 7.2 Abstract

As simulation-based training becomes more standardized in the field of neurointervention, there is an opportunity to provide simulated image fusion to improve navigational competency. This can provide visual reference data during simulated endovascular imaging, potentially improving the ability to interpret contrast-enhanced fluoroscopic images and manipulate endovascular wires. This technique could be especially beneficial for novices and individuals with low mental rotation skills.

In this study, 17 medical students were recruited through internal messaging platforms at Western University. Participants completed an orientation module and training package prior to being randomly assigned to either a control or intervention group. The intervention group had access to an anatomy overlay feature during the simulated angiography procedure. Participants completed weekly repeating sessions over 6 weeks, with the exception of the final session, which included a novel clinical case and vascular objective.

Total procedural time decreased significantly in all testing groups across the first 5 sessions. Control group participants with low MRT finished comparatively slower as limited imaging through fluoroscopy did not provide enough navigational context, however, they excelled in the intervention group, outpacing their high MRT counterparts when they received access to complementary anatomy overlay tools. At the final session using a novel case, the control group suffered significantly in procedural time, while the intervention group had maintained its performance improvement. The use of fluoroscopy was significantly lower in the intervention group, however, this difference was supplemented by the availability and use of anatomy overlay.

It appears that using simulated image fusion to provide visual reference data during simulated endovascular imaging can improve navigational competency and reduce procedural time in medical students, particularly those with low mental rotation skills. This technique was found to be especially beneficial when used in combination with anatomy overlay tools. Overall, the use of simulation-based training with simulated image fusion and anatomy overlay tools appears to be a promising approach to improving navigational competency in neurointervention.

## 7.3 Background

The pathway to competency in surgery constitutes the accumulation and interfacing of a wide set of technical and non-technical skills. As subspecialties have progressed in their complexities, so have their needs for complementary training. Simulation has become a cornerstone for the refinement of complex surgical skills, and in its increasing abundance, has offered the challenging consideration – what kind of complementary assistance should be provided for the development of the variety of subsets of skills required for surgery? This is a question that needs to be thoroughly measured in simulation-based training for cerebral angiography procedures which involves a unique combination of motor, visuospatial and imaging skills.

Acquisition and refinement of technical skills in simulation-based surgery training have been shown to benefit from a variety of training interventions including verbal expert debriefing (Chetlen et al., 2015; Savoldelli et al., 2006), visual guidance (Maya Dreier Sørensen et al., 2017), haptics (van der Meijden & Schijven, 2009). Visual guidance in the form of gaze channels (Leff et al., 2015), depth reference (Wagner & Rozenblit, 2017) and 3D visualization of vascular anatomy (Masutani et al., 1998; Wang et al., 2012), has been shown to provide more benefit in surgical training than verbal feedback and has been implemented in a variety of training modalities to facilitate the interpretation of imaging (Leff et al., 2015; Masutani et al., 1998; Maya Dreier Sørensen et al., 2017; Wang et al., 2012).

Cerebral angiography training can significantly benefit from these tools to conquer the variety and complexity of spatial, motor and imaging interpretation skills. Simulation-based training has been shown to improve navigational skills (Zaika et al., 2020) and diagnostic metrics (Zaika et al., 2016), however, the learning curves were still stunted by complexity of some vascular imaging (ie. Understanding the bifurcation of external and internal carotids) and lower scores in mental rotation capabilities. Although simulation provided by the ANGIO Mentor provides great realism through its haptic engine and tool manipulation, imaging use and dynamics, the fundamentals of interpreting fluoroscopic imaging may be a large roadblock for new trainees.

The consideration now revolves around the appropriate use of available tools for the facilitated acquisition of navigational skills for trainees. Vascular image fusion is a novel imaging modality that overlays detailed CT or MR angiography imaging over fluoroscopic imaging to provide dimensionality and context for vascular navigation (Ahmad et al, 2018, Schwein et al., 2018). However, these modalities are not always available as they require the use of multiple imaging platforms and computation for their synthesis.

As simulation-based training becomes more standardized within this specialty, there is an opportunity to provide simulated image fusion to accelerate navigational competency in neurointerventionalists. Based on the benefit visual assistance has been able to provide for imaging interpretation, we had hypothesized this effect would also be seen in simulation-based cerebral angiography training by facilitating the interpretation of the cerebrovascular network and improving navigational proficiency in novices.

## 7.4 Methods

### 7.4.1 Participants

Participants were recruited through internal messaging platforms at the Schulich School of Medicine and Dentistry, Western University. The invitation to participate specified the characteristics of study, including the environment, length of study, and pre-requisite of no previous experience with angiography, and did not specify the parameters of anatomy overlay use. A total of 17 medical students were recruited for the study. This study was completed in accordance with the Western University Health Science Research Ethics Board (HSREB#: 102917) (Appendix B).

### 7.4.2 Cohort Intake

All participants completed an orientation module that included study background information and demographic survey (1), timed mental rotations test (2), anatomy and angiography learning module and knowledge test (3), and cerebral angiography and simulator tutorial (4).

(1) The demographic survey included questions about gender, age, handedness, surgical experience, and cerebral angiography familiarity. This survey was used to identify and exclude participants who did not meet the requirement of inexperience for participation.

(2) A two-part, timed mental rotations test (MRT) (Vandenberg and Kuse,1978) was distributed upon completion of the intake demographic survey. Each 3-minute, 12-question part required participants to identify two rotated matches out of four options to a sample image.

(3) All participants were given free time to individually review a standardized anatomy and angiography learning module. This training package included information on procedurally-relevant vascular anatomy, including names and positions of vessels from the aorta to the circle of Willis, aneurysm locations and treatments, and cerebral angiography techniques and imaging. Once participants felt comfortable with the reviewed material, an untimed 10-question anatomy and angiography test was distributed. A score of 80% was required to be included in the study. In the result of a failing score, the participant would be required to restart the learning module.

(4) An instructional simulation booklet was created for participants to ensure consistency in familiarity with the equipment. The booklet included information about all accessible buttons on the physical simulation console, visual layout of the monitors, and functionality of pedals. Participants were also provided with a guided tour through the simulation software, including information available in the booklet.

Participants were randomly assigned to either control or intervention groups at study intake. Groups were controlled for equal distribution of low and high MRT scoring individuals. Due to the number of participants in this study, we did not control for any other factors between groups.

### 7.4.3 Simulation Environment

The simulation equipment was set up in a private office within the university hospital to minimize distractions, such as noise. The simulator and associated monitors were set up on an office desk which could be operated in a seated position, as intended and prepared by simulation manufacturer. Foot pedals were available underneath the desk. Researcher was seated behind the participant during data collection.

The ANGIO Mentor Express (3D SYSTEMS) was used for all training and testing protocols listed in the study. This haptic virtual reality simulator provides tactile and visual feedback representative of the environment found in the Angio Suite, including imaging monitors, pedals and endovascular access site.

### 7.4.4 Study Design

Groups

Participants were equally divided into control and intervention groups. Both groups received the same amount of training, exposure to tools, clinical case exposure and guidance. The control group had access to all procedural tools and imaging modalities used in diagnostic angiography, such as fluoroscopy and digital subtraction angiography. The intervention group had access to all tools supplied to the control group, with the addition of an anatomy overlay feature (Figure 19). The anatomy overlay feature allowed for the visualization of vascular anatomy without the use of fluoroscopy, and provided colour, shading, and rotational views not available in fluoroscopic imaging. The intervention group was given full control over the engagement of the anatomy overlay feature, but was encouraged to only use this assistive function when the vascular anatomy in fluoroscopic imaging was unclear or when the participant felt 'lost' in their trajectory to the aneurysm.

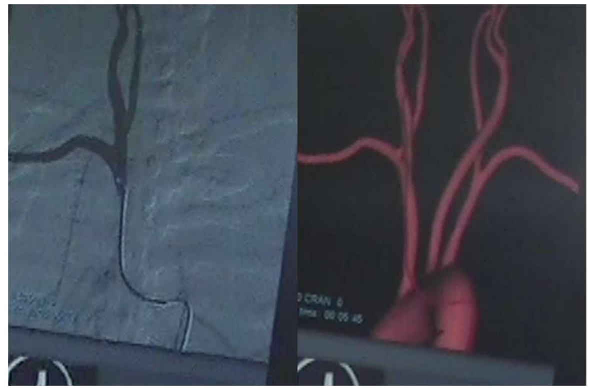

**Figure 19 – Simulated angiography with anatomy overlay**
**Comparison of the visualization of vasculature using contrast and fluoroscopy (left) and anatomy overlay (right).**

Sessions

Participants attended 6 training/testing sessions over the course of 6 weeks. The first session included a tutorial on simulator functions and tools. Participants were given an opportunity to get to know the simulator with hands on practice prior to their first testing session. With the exception of the last session, each session consisted of an untimed practice case using left-sided vascular anatomy (left internal carotid aneurysm) in order to ensure participant had the proper understanding of the steps and tool use, followed immediately by a timed test case using right-sided vascular anatomy (right middle cerebral artery (right middle cerebral aneurysm). Participants had access to an instructional sheet, but were only provided with verbal assistance during their practice case. Participants were instructed to finish and exit out of their simulated case when they had deemed all instructional steps were completed and the appropriate neurological images had been taken.

The final session included a practice case identical to previous sessions, followed by a novel test case requiring a different navigational trajectory on the right-sided anatomy than that of previous test cases (right vertebral artery aneurysm). The intervention group was not provided the anatomy overlay function for their final test session.

### 7.4.5 Data Collection

All technical performance data was extracted from the simulation software. Similar to other studies assessing the simulator, an overall procedural speed/pace was used as a marker for performance improvement.

### 7.4.6 Data Analysis

The Statistical Package for Social Sciences (SPSS 18.0; SPSS Inc, Chicago, Illinois) was used to analyze the data. A two-way repeated measure analysis of variance (ANOVA) was used to analyze performance between the two testing groups. A two-way repeated measures ANOVA was used for MRT comparisons.

### 7.4.7 Learning Index

A standardized learning index (Gallagher et al., 2015; Pereira & Burwell, 2015) was used to compare the inter-group skill acquisition to identify differences or lack there-of. A unique session multiplier was calculated for each session through a fractional ratio of control group performance in that session to the first session. The learning index was then calculated by applying the session multiplier to the sum of scores in both groups. This created a normalized performance score – the learning index – for each participant that can be used to make comparative assessments on process learning.

### 7.4.8 Intravascular Tool Location

The location logging capability of the simulator was used to calculate the timestamps at which vascular branches were accessed and exited by the main navigation tools (guidewire and catheter). The timestamps were used to calculate cumulative time spent in vessels that were not on the most direct path to the suspected aneurysm site. For sessions 1-5, since the aneurysm was expected to be off the right middle cerebral artery, the correct navigational pathway only included the aortic arch, brachiocephalic trunk, right common carotid artery and right internal carotid artery. The incorrect vasculature for sessions 1-5 included the left subclavian artery, left common carotid artery, right subclavian artery, right vertebral artery and right external carotid artery. For session 6, since the aneurysm was expected to be off the right vertebral artery, the correct navigational pathway only included the aortic arch, brachiocephalic trunk, right subclavian artery and right vertebral artery. The incorrect vasculature for session 6 included the left subclavian artery, left common carotid artery, right common carotid artery, right internal carotid artery and right external carotid artery.

## 7.5 Results

### 7.5.1 Total Procedure Time

Consistent with previous data assessing the improvements in performance by novices trained on ANGIO Mentor clinical cases, there was a significant decrease in total procedural time in all testing groups across the first 5 sessions (Figure 20). Along with the sharp improvement, there was also a marked reduction in outcome variance as study participants performed more consistently within their group. Unsurprisingly, the highest performers within the control group were those that had the highest scores on the MRT, as this visuospatial score has been

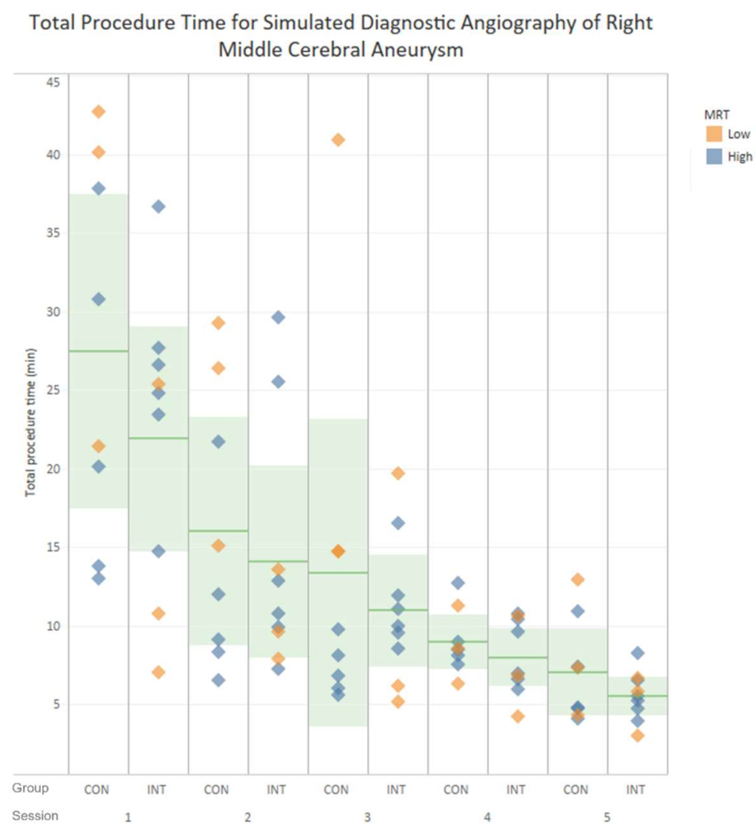


**Figure 20 - Procedural time for assisted and control novices, repeat cases**

**The total procedural time for sessions 1-5 shows the comparative improvement in performance by the control (CON) and intervention (INT) groups. The individual performances can be identified to low MRT-scoring subgroup (orange) and high MRT-scoring subgroup (blue). The standard deviation in scores is identified by green shading, with the green line indicating session average.**

shown to be a predictor in performance for highly spatial tasks performed in this study. Control group participants with low MRT finished comparatively slower as limited imaging through fluoroscopy did not provide enough navigational context, however, they excelled in the intervention group, outpacing their high MRT counterparts when they received access to complementary anatomy overlay tools. Without taking MRT into account, both control and intervention groups performed similarly on the first 5 sessions.

At the final session using a novel case, the control group suffered significantly in procedural time, while the intervention group had maintained its performance improvement (Figure 21).

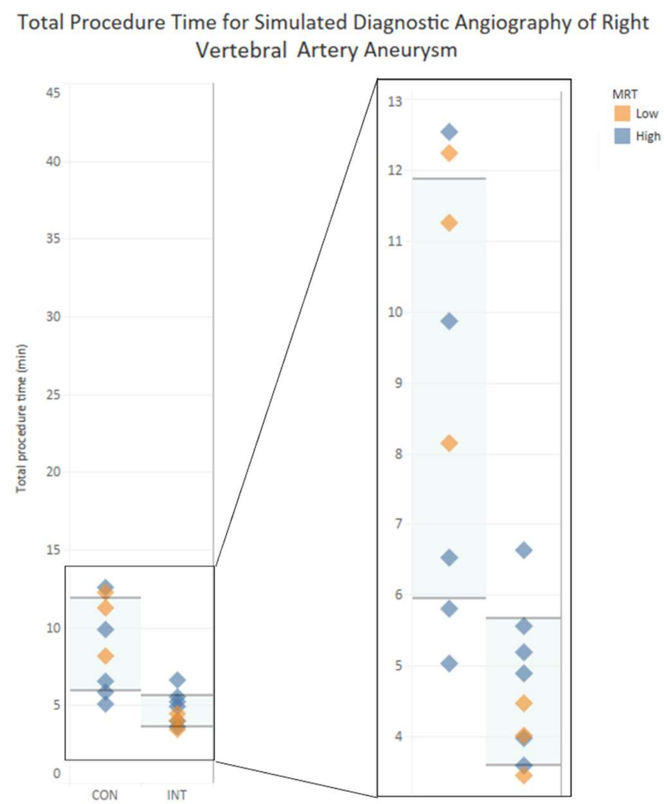


**Figure 21 - Procedural time for assisted and control novices, new case**

**The total procedural time for sessions 6 shows the comparative improvement in performance by the control (CON) and intervention (INT) groups. The individual performances can be identified to low MRT-scoring subgroup (orange) and high MRT-scoring subgroup (blue).**

### 7.5.2 Learning Index

Calculations of the learning index showed a comparatively equal distribution of performance improvements by each individual participant, exemplified by the learning index score (Figure 22). This score, normalized to the control group performance, is consistent with the relatively equal changes in performance by both groups between sessions 1-5.

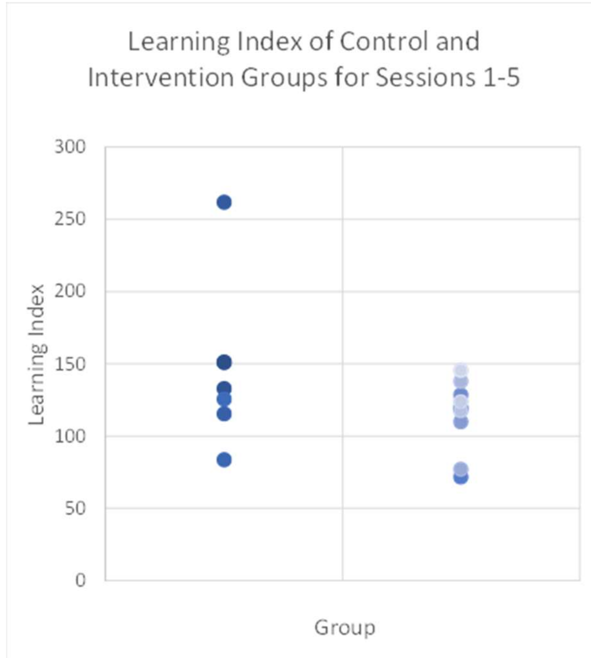


**Figure 22 - The learning indices for the control (CON) and intervention (INT) groups' participants are comparatively equal for sessions 1-5.**

### 7.5.3 MRT Groups

There was no significant difference between low and high MRT groups over the course of the study. Low MRT participants tended to have more variability in performance in the first session and had generally longer procedural times throughout the sessions. Low MRT group had also suffered the most in performance on the final session, compared to the high MRT group (Figure 23).

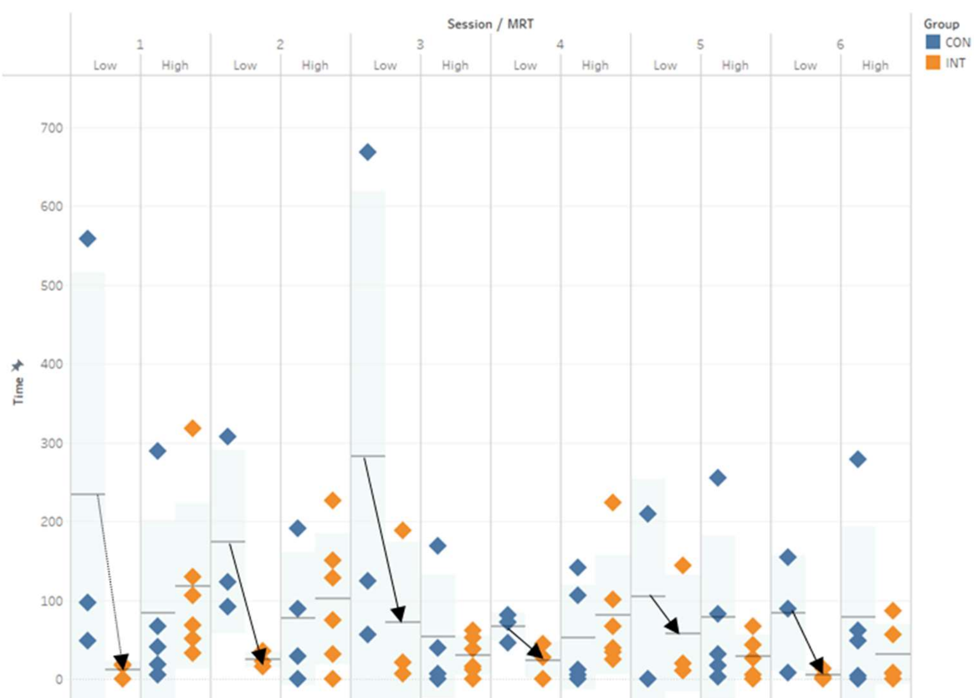


**Figure 23 – MRT group performances compared to intervention**

**Segmenting by MRT group and intervention group showed a pattern of increased impact of anatomy overlay access in the intervention group for those with low MRT, however, the groups were too segmented for a statistically significant difference.**

### 7.5.4 Fluoroscopy and Anatomy Overlay Use

Assessment of image visualization modalities between groups (

Figure 24) revealed a pattern of improved scores similar to that of total procedure time (Figure 21). The use of fluoroscopy was significantly lower in the intervention group, however, this difference was supplemented by the availability and use of anatomy overlay. The cumulative use of both visualization tools by the intervention group seems to indicate an ongoing need for updated vascular views, similar to the need of the control group. However, the significantly improved performance by the intervention group on session 6 (Figure 20), may indicate better learning and retention of vascular information via similar vascular exposure times.

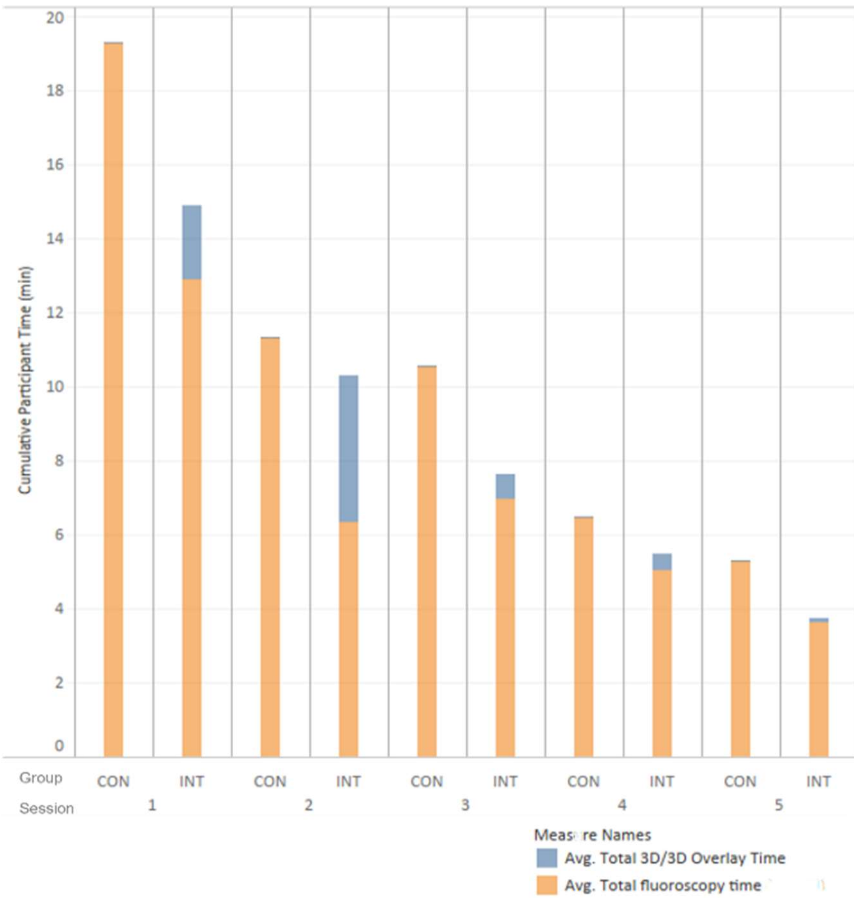


**Figure 24 – Visualization time of vasculature**
**Cumulative vasculature visualization through the use of fluoroscopy (orange) and anatomy overlay (blue) was similar in both groups across sessions 1-5.**

## 7.6 Significance

As we had hypothesized, the effect of providing the anatomical overlay during training was really seen during the final session, when all participants had a brand new unexpected case, and the intervention group, whose learning was facilitated by visual overlay in previous sessions, was able to maintain their procedural time performance, while the control group struggled. Even though surgical training needs to provide variety and difficulty, we have seen that in repeated case training, providing visual assistive resources can improve procedural learning and adaptability to uncertain clinical scenarios.

In previous assessments we had seen the significant role that MRT plays in the learning curve of spatially tasking tasks, such as angiography. Due to the segmentation of the cohorts in this study, and the subsequently shrunken analysis groups, we were not able to see significant differences in performance. In the future, a study with a high sample may be able to shine a light on the amount of visuospatial assistance low and high MRT individuals can benefit from in this particular type of exposure.

## 7.7 Conclusion

The results of this study show that the use of anatomy overlays in simulation-based training can significantly improve performance and reduce procedural time in novice trainees. Additionally, the use of these overlays was found to be particularly beneficial for individuals with low mental rotation ability, indicating the importance of providing visualization tools to improve navigational competence in these individuals.

It would be useful to conduct further studies to assess the benefits of providing visual anatomy overlays during simulation-based training for neurointerventionalists. This could include a larger study with more participants, and could also focus on evaluating the translation of skills learned in simulation into the Angio Suite, to determine the potential of simulation-based training in improving patient outcomes. Additionally, research could be conducted to identify which individuals would most benefit from visual anatomy overlays, and to determine the optimal amount of assistance to provide. These studies could help to establish a standardized training curriculum using simulation-based training and visual anatomy overlays, and could ultimately improve the quality of care for patients undergoing neurointerventional procedures.

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# 8 Aim 4 - Simulation-Based Cerebral Angiography Coiling Training in Novices

## 8.1 Contributors' Statements

OZ was responsible for participant recruitment, data collection and interpretation, data visualization, and manuscript preparation. MB revised data collection tools, interpretation of collected data and revised manuscript draft. RE revised data collection tools, assisted in interpretation of collected data, and revised the manuscript draft. SR designed data collection tools, monitored the data collection progress, and revised the manuscript draft. All members of this study had a strong role in study design.

## 8.2 Abstract

Endovascular surgical procedures require visual-spatial coordination in workspaces with restricted motions and temporally limited imaging. The development of the skills needed for these procedures can be facilitated by 3D simulator-based training. Cerebral angiography (CA) has lagged behind in this training approach due to the lack of validated, realistic training models, relying strictly on clinical case exposure frequency ('number of hours logged') as a means of assessing proficiency. The ANGIO Mentor visual-haptic simulator is regarded as an effective training tool, however, this simulator has not been tested thoroughly in its ability to train interventional skills. In particular, the details of the aneurysm coiling process during autonomous simulation-based training haven't been assessed.

In this study, 12 novice medical students were given simulation-based diagnostic cerebral angiography training until a procedural plateau in performance, established in our previous work. Subsequently, they were trained using video tutorials and written instructions to identify, measure and intervene with cerebral aneurysms using endovascular coils. Over the span of 6 sessions, participants were assessed on their procedural task time, coiling quantity and quality, and perforation rates. Prior to commencing the study, participant spatial ability was assessed using a mental rotation test (MRT) and used as a comparative baseline for the performance analysis.

We found that all individuals were able to perform the procedure faster after 6 sessions, reducing their average time from 42 to 24 minutes. Coil success rate improved over from 82% to 88% and coil packing rate remained consistent at 30% throughout testing. High perforation rate seen at the start of the study showed a trend of decreasing over the latter sessions, however, over half of aneurysms were still being perforated by the novice participants. No change in aneurysm coiling quality was found, with a slight decrease in number of parent artery coil protrusions. High MRT individuals were better able to establish necessary tools prior to coiling, however, no other MRT-specific changes were seen.

This work identifies the utility of simulation-based cerebral angiography training in identifying the particular difficulties trainees experience in learning procedural skills, including prevention of perforations, proper positioning and success of coils within the aneurysm.

## 8.3 Introduction

The development of necessary technical motor and spatial skills is one cornerstone of clinical training, and unsurprisingly, a significant obstacle to qualifying as a competent interventional radiologist. Complex, minimally invasive procedures, such as endovascular coiling of cerebral aneurysms, require extensive procedural training which is increasingly limited by restricted working hours(Dawson, 2006; Okuda et al., 2009), elevated operating costs (Bridges & Diamond, 1999) and shortened diagnostic exposure (Gould, 2007; Gould et al., 2006). These pressures, compounded by the push for competency-based medical education (Chetlen et al., 2015) and ever-rising standards of care, have made traditional apprenticeship training methods less effective (Napolitano et al., 2014).

Simulation is offered as a potential solution to training concerns, however, despite leaps in technological advancements, its adaptation has been limited. Validation studies have provided evidence for increased training efficacy using simulation (Nguyen, Eagleson, et al., 2014), however, the development has faced challenges in explaining how it can replace the current gold standard - learning on patients. Some of the highest fidelity simulators on the market, including the VIST-C simulator system by Mentice and the ANGIO Mentor by Simbionix, have made strong advances in replicating the haptics and procedural dynamics of cerebral angiography to bridge this gap. Research in simulation-based angiography training has shown to improve some aspects of technical performance, such as fluoroscopy use (A. H. Kim et al., 2015; Zaika et al., 2016) and fluidity of motion (Estrada et al., 2016; Estrada & Malley, 2014), however, the effectiveness of its integration can be improved with a better understanding of the core skills it impacts.

Diagnostic angiography is used to endovascularly locate the aneurysm and identify its risk for hemorrhage and need for intervention. Subsequently, if necessary, based on the assessment, interventional angiography allows interventionalists to treat the aneurysm, usually through the deposition of electrolytic coils which fill the space to reduce blood (Figure 25). In the clinical setting, aneurysm coiling involves a wide array of technical skills necessary for successful intervention. Finely tuned motor skills allow interventionalists to manipulate endovascular wires while matured spatial skills allow them to interpret 2-D imaging necessary for navigation. During aneurysm intervention, careful placement, electrolytic detachment and stabilization of coils requires a firm grasp of the tools' mechanical dynamics (Zanaty et al., 2014). The ability to mentally rotate fluoroscopic images allows not only for the accurate navigation of endovascular environments, but also for the appropriate placement of coils within a 3-D space. As a result, mental rotation tests are administered in conjunction with technical surgical assessments to help explain performance differences and training needs.

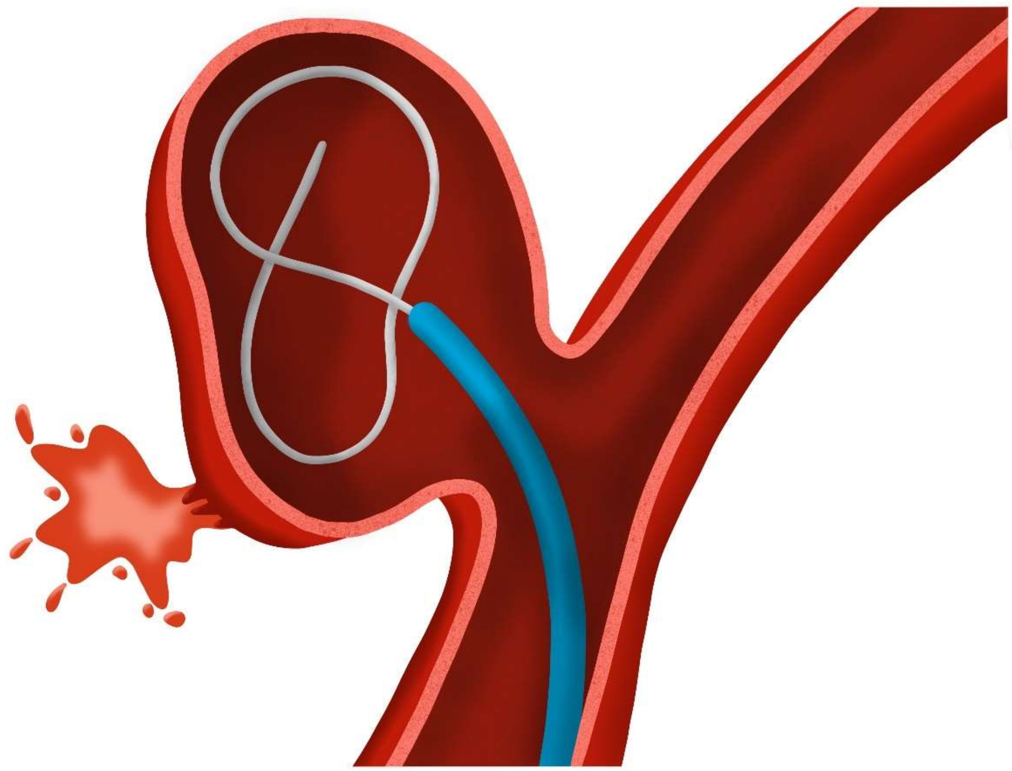

**Figure 25 – Coil placement within a saccular aneurysm**
**Many factors affect the quality and success of a cerebral aneurysm coiling procedure including microcatheter placement, coil positioning, rupture and hemorrhaging avoidance, coil size selection, and balance of coils within the aneurysm space.**

The complexity of the coiling process has left the procedure without standardized performance standards, and the measure of its success in the hands of the interventionalist. A thorough analysis of trainable technical skills in coiling would provide some clarity and direction, which is imperative for the creation of standardized performance assessments and thresholds.

Technical skills in aneurysm coiling are the backbone of the graded success of the procedure and the resulting patient outcomes. Procedural time is a basic marker used to quantify performance in this field as it suggests higher clinical competency and results in lower operating costs (Crofts et al., 1997). Of course, procedure times must be examined in conjunction with the accuracy and error rates of the task. Subsets of skills that generate faster interventionalists are not well studied and could explain which competencies are necessary for such improvement. Since the placement of coils in the aneurysm space is such a careful and repetitive task, small improvements in each cycle can accumulate into larger gains.

The appropriate number of coils deposited into the aneurysm has a direct relationship to the duration of the coiling process (Vanzin et al., 2012), however, it is not currently measured as a marker for operating quality. Furthermore, time delays associated with exchange of incompatible coils can further inform these markers. Prevention of adverse outcomes, such as coil protrusion(Doerfler et al., 2006) and aneurysm perforation(Kallmes & Cloft, 2012), can also grade operating quality through improved patient outcomes.

A query still stands: is it possible to make implementation of simulation-based training more purposeful by better understanding which technical skills it most helps develop? The objective of the study was to quantify the degree of core technical skill development in novice cerebral aneurysm coiling trainees when exposed to low risk, high frequency simulation-based training. The aim was to clarify technical skills involved in the intervention and quantify performance improvements in self-regulated simulation practice.

## 8.4 Methods

### 8.4.1 Participants

To ensure training novelty, only participants with minimal or no knowledge of endovascular skills and basic vascular background were included. The Schulich School of Medicine and Dentistry Hippocratic Council, a student-run society for medical students at the University of Western Ontario, London, Ontario, Canada, distributed a call-out for participation via an internal messaging system. A total of 20 students replied to the flyer and initiated training in the study. At the end of the 4-month study period, 12 of the initial 20 participants completed the study. This study was approved by and completed in accordance with the Western University Health Science Research Ethics Board (HSREB#: 104787) (Appendix A).

### 8.4.2 Participant Orientation

All participants completed an orientation module that included study background information and demographic survey (1), timed mental rotations test (2), anatomy and angiography learning module and knowledge test (3), and cerebral angiography and simulator tutorial (4).

(1) The demographic survey included questions about gender, age, handedness, surgical experience, and cerebral angiography familiarity. This survey was used to identify and exclude participants who did not meet the requirements of inexperience for participation.

(2) A two-part, timed mental rotations test (MRT) was distributed upon completion of the intake demographic survey. Each 3-minute, 12-question part required participants to identify two rotated matches out of four options to a sample image.

(3) All participants were given free time to individually review a standardized anatomy and angiography learning module. This training package included information on procedurally-relevant vascular anatomy, including names and positions of vessels from the aorta to the circle of Willis, aneurysm locations and treatments, and cerebral angiography techniques and imaging. Once participants felt comfortable with the reviewed material, an untimed 10-question anatomy and angiography test was distributed. A score of 80% was required to be included in the study. In the result of a failing score, the participant would be required to restart the learning module.

(4) An instructional simulation booklet was created for participants to ensure consistency in familiarity with the equipment. The booklet included information about all accessible buttons on the physical simulation console, visual layout of the monitors, and functionality of pedals. Participants were also provided with a guided tour through the simulation software, including information available in the booklet.

### 8.4.3 Simulator Type

The ANGIO Mentor Express (3D SYSTEMS) was used for all training and testing protocols listed in the study. This haptic virtual reality simulator provides tactile and visual feedback representative of the environment found in the Angio Suite, including imaging monitors, pedals and endovascular access site (Figure 26).


**Figure 26 – Simulation set-up using the ANGIO Mentor Express**

**The ANGIO Mentor Express simulation set up provides the haptic representation of endovascular access (simulator console, left), imaging monitors (right), and imaging pedals (not pictured).**

### 8.4.4 Simulation Environment

The simulation equipment was set up in a private office within the university hospital to minimize distractions, such as noise. The simulator and associated monitors were set up on an office desk which could be operated in a seated position, as intended and prepared by simulation manufacturer. Foot pedals were available underneath the desk. Researcher was seated behind the participant during data collection.

### 8.4.5 Simulated Case

ANGIO Mentor cases included in the license were used to create the training and assessment scenarios. The cases include a patient file with basic clinical information regarding suspected aneurysm location and associate complications. A left-sided internal carotid artery aneurysm case (Case File #1) was used for the training scenarios and a right-sided middle cerebral artery aneurysm case (Case File #5) was used for the assessment scenarios. These cases were chosen to ensure that training scenarios were simpler and used different vascular anatomy compared to the assessment scenarios.

A booklet with the procedural outline, including tools, actions, and objectives, was available to guide case completion. An endovascular guidewire and catheter were set up partially inserted into the simulator. During interventional angiography, the insertion of the guiding catheter into the simulator was assisted by the researcher to accommodate the simulator calibration process.

Simulated scenarios commenced with a prepared virtual patient in supine position and imaging focused on the thoracic aorta where inserted tools are first simulated. Following the case outline and instructional booklet, participants navigated through the endovascular environment by inserting and rotating wires and catheter within the simulator console.

Assistance, such as answering questions and giving direction, was only included during the training scenario. The assessment scenario progress and completion were independently guided by the participant.

### 8.4.6 Instructional Design

Two separate training-assessment stages were used for data collection: (1) diagnostic angiography and (2) aneurysm coiling. Diagnostic angiography stage included eight weekly sessions, each comprised of a training and subsequent assessment scenario. Upon the completion of all diagnostic angiography sessions, the aneurysm coiling stage commenced with an introduction to coiling module, followed by 6 weekly sessions using the training/assessment paradigm described previously. In all sessions, each set of cases could be performed only once, and no limit to case completion length was set. Due to the lack of availability of cases, there was no variation in clinical or scenario context between sessions.

### 8.4.7 Data Collection and Analysis

A basic performance overview was made available to the participants upon completion of the assessment scenario, which included procedural pace, aneurysm filling density, coil deployment quantities, imaging frequency and contrast use. A brief informal discussion about the statistics took place with the researcher at this time.

The Statistical Package for Social Sciences (SPSS 18.0; SPSS Inc, Chicago, Illinois) was used to analyze the data. A one-way repeated measure analysis of variance (ANOVA) was used for procedural time, coil use efficiency, and aneurysm perforation rate. A two-way repeated measures ANOVA was used for MRT comparisons.

### 8.4.8 Outcomes

All technical performance data was extracted from the simulation software. Similar to other studies assessing the simulator, an overall procedural speed/pace was used as a superficial marker for performance improvement. In addition, a variety of indices of performance were also used to assess, on a deeper level, the potential reasons for changes seen in procedural pace. These indices included number of coils used to fill the aneurysm, including number of coils successfully deposited and coils discarded due to incompatibility. Concurrently, aneurysm packing density was used to ensure sufficient aneurysm volume was filled with coils. Major errors, such as coil protrusion into parent artery and aneurysm wall perforation, were quantified alongside other markers.

During the diagnostic angiography stage, only procedural pace was assessed. This data was used to ensure participants had necessary baseline performance to proceed to interventional angiography.

## 8.5 Results

All participants successfully passed the qualifying anatomy and angiography module on the first attempt. The following subsections describe the different aspects of performance on the overall procedure:

### 8.5.1 Overall Pace

Similar to results seen in other studies assessing overall simulation-based performance(A. H. Kim et al., 2015; Alejandro. Spiotta et al., 2011; Willaert et al., 2012; Zaika et al., 2016), diagnostic angiography (DA) procedural time dropped significantly ($p<0.05$) over a span of eight training sessions (Figure 27). After reaching a procedural plateau in the diagnostic angiography stage, participants had high procedural times and standard deviation at the first interventional angiography session, also seen at the first diagnostic angiography training session. Participants completed the first full interventional angiography ($IA_1$) session in an average of 42 minutes and improved to 24 minutes by the last session ($IA_6$)($p<0.05$)(Figure 28).

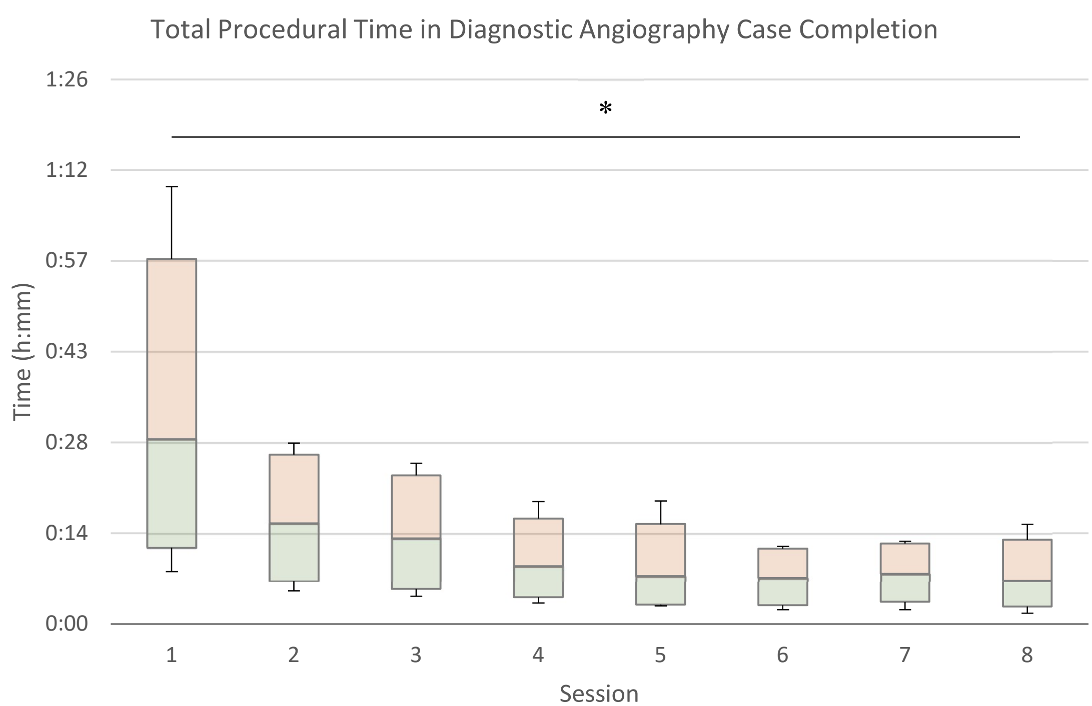


**Figure 27 – Procedure time in simulated diagnostic angiography case**
**A significant decrease (*$p<0.05$) in procedural time was observed between $DA_1$ and $DA_8$, consistent with results seen in previous studies. Concurrently, a plateau of performance is observed between $DA_5$-$DA_6$, identified as a non-significant change ($p>0.05$) in procedural time. The interquartile range is represented by combination of red (3rd quartile minus median) and green (1st quartile minus median).**

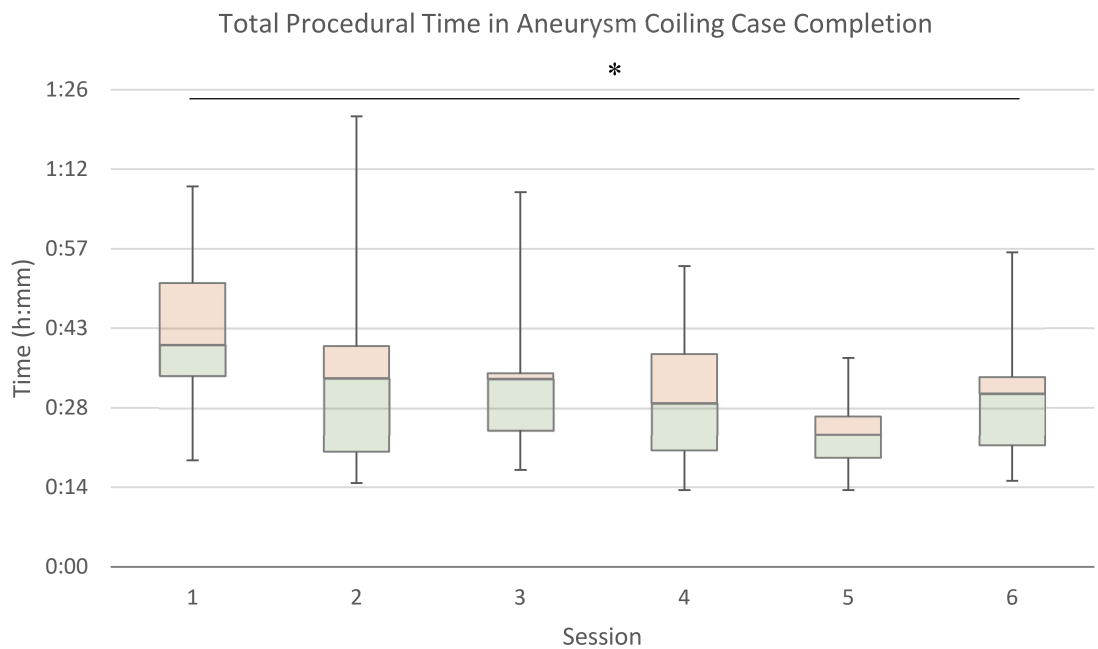


**Figure 28 – Procedure time in simulated interventional angiography case**
**A significant decrease in procedural time is seen in 6 sessions of simulation-based training and testing (*p<0.05). Slower novice performers (3rd quartile minus median = red) improve their pace to cluster with the higher performance group (1st quartile minus median = green) by the end of training.**

### 8.5.2 Coiling Success

At $IA_1$, an average of 12.45 coils were used to fill the aneurysm completely and 2.64 coils were being discarded due to poor fit, resulting in an 82% success rate of detaching inserted coils. At the completion of the study ($IA_6$), an average of 11.08 coils were needed to fill the aneurysm and only 1.46 coils were being wasted, resulting in an 88% success rate (Figure 29).

Participants were able to maintain a 30% packing density in the aneurysm space throughout all sessions, consistent with density requirements in a real clinical case.

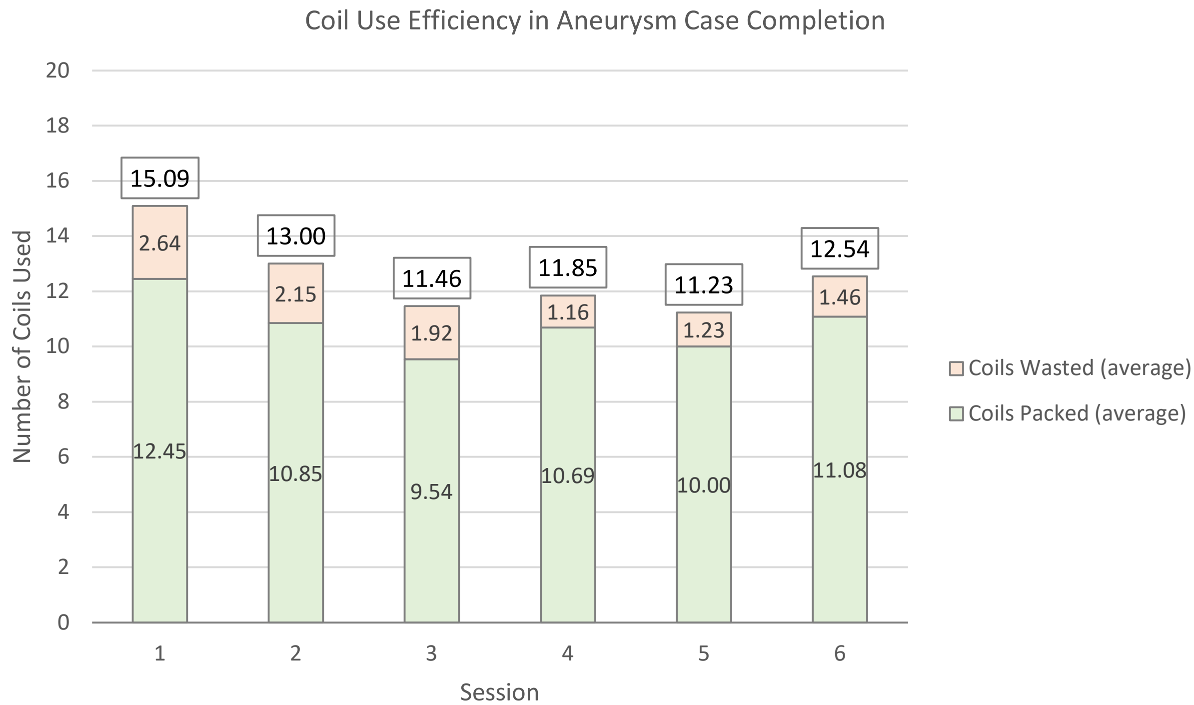


**Figure 29 – Endovascular coil use by novices in simulated case**
**The number of coils used to fill the aneurysm decreased from 15 coils at the first interventional angiography session to 12.5 by the last. This reduction, although not statistically significant, may have been inclusive of reductions in coils waste and coils packed.**

### 8.5.3 Coiling Errors

Participants improved placing coils within the aneurysm boundaries without protrusions into the parent artery, with 4 recorded protrusions at $IA_1$ (2.5%/case) and no protrusions at $IA_6$ (Figure 30).

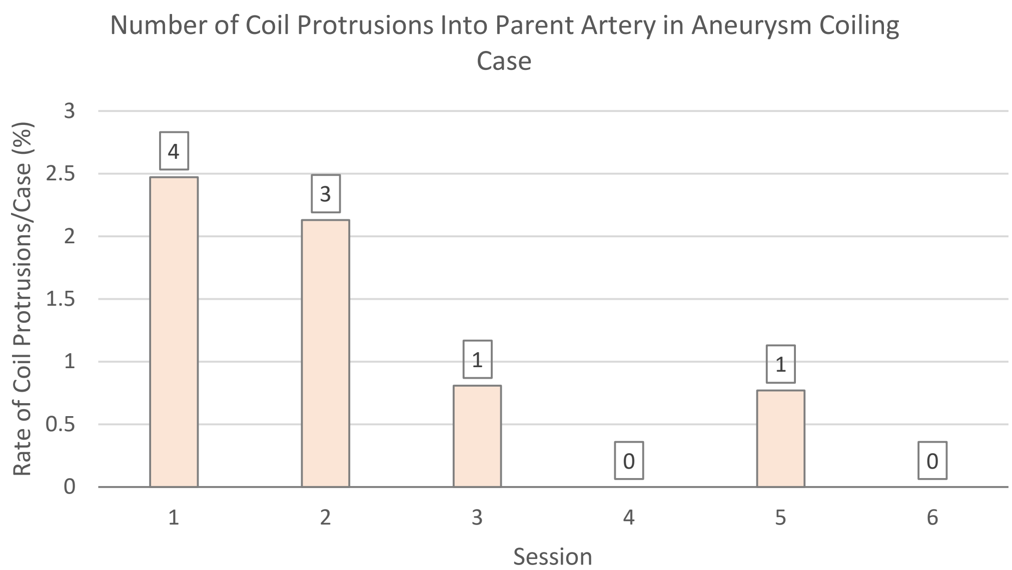


**Figure 30 – Coil protrusions by novices in simulated case**
**The total number of protrusions of coil out into the parent artery reduced from 4 across all participants to 0 by the end of the study.**

Aneurysm perforation rates maintained at 77% for the first 4 sessions ($IA_{1-4}$), but improved to 54% by $IA_6$. By the completion of the study, only 46% of participants were successfully coiling the aneurysm without perforating the vascular wall during intervention (Figure 31).

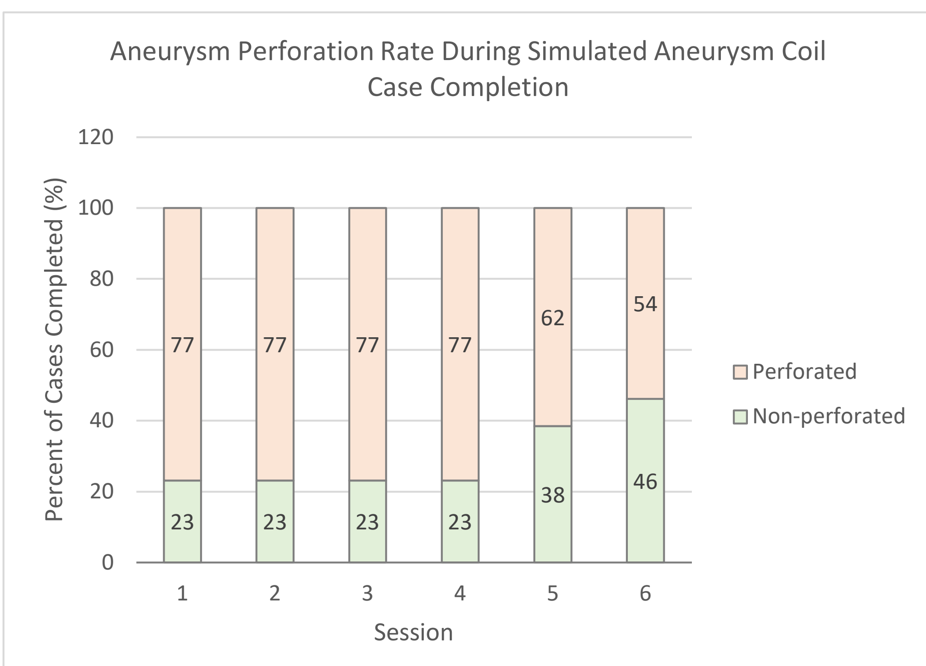


**Figure 31 – Aneurysm perforations by novices in simulated case**
**The rate of aneurysm perforations reduced from 77% at IA1 to 54% at IA6.**

### 8.5.4 Spatial Ability

Low MRT individuals performed significantly ($p<0.05$) slower than high MRT individuals, starting aneurysm coiling in $IA_1$ at 22 minutes and $IA_6$ at 13 minutes, compared to high MRT at 12 minutes and 7 minutes, respectively (Figure 32).

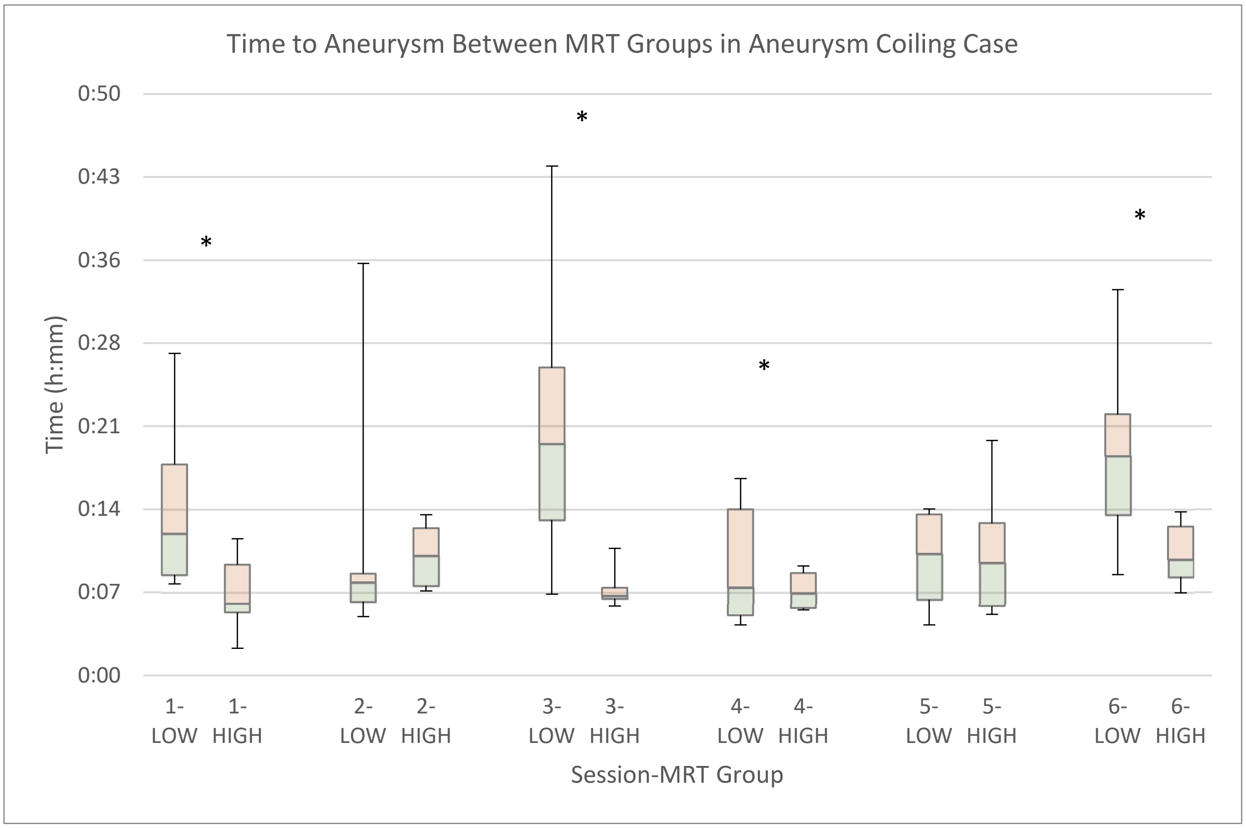


**Figure 32 – Comparison of MRT and navigation time to aneurysm**

**Individuals with low MRT performed significantly worse (*$p<0.05$) than those with high MRT overall across the coiling sessions, however, comparting within each session, a significant difference was only seen in sessions $IA_1$, $IA_3$, $IA_4$, and $IA_6$ due to variability of performance in sessions $IA_2$ and $IA_5$.**

## 8.6 Discussion

### 8.6.1 Technical Skills in Coiling

Technical skills necessary for minimally invasive procedures are incredibly fine-tuned and precise, creating the need for rigorous hands-on training. The results in this study advocate for the potential of high-fidelity simulation training to offset the duration of introductory practice in the operating room. As seen in previous work, the procedural pace is markedly improved within the simulation environment and may be associated with increased performance in key high-risk maneuvers during coiling. Since aneurysm coiling uses progressively smaller coils to fill the space, the ability of novices in this study to maintain filling capacity while reducing the number of coils inserted and discarded implies a fine proficiency in estimating the needs of the aneurysm environment. At an average of 11 coils used to fill the narrow 9mm aneurysm, their performance in this regard falls within the range of proficient interventionalists, who average 8.2 ± 3.8 coils/aneurysm of this scale (8.6 +/- 1.6mm). The novices' ability to gauge the 30% filling setpoint correctly, which clinically is seen as a sufficiently filled aneurysm, reinforces their apparent technical skill maturity.

The decreasing rate of committed coiling errors observed throughout the study was encouraging, however, it is hard to translate these results to clinical training as these incidence rates would not be permissible in the Angio Suite. The elimination of accidental coil protrusions into the parent artery from 0.33 rate seen in $IA_1$ indicates an improved ability to manipulate the microcatheter to better position the expanding coils. Concurrently, the decreasing rates of aneurysm wall perforation are encouraging, but the residual error rate may be limited by the self-regulated practice established in the methodology and may require guided debriefing with an expert in order to improve significantly.

### 8.6.2 Role of MRT

Spatial ability has been thoroughly studied and correlated with novice surgical performance(Clem et al., 2013; Keehner et al., 2004). The markedly improved pace individuals with high MRT were able to achieve establishes MRT as another potential marker for assessing trainee needs. Future interventionalist fellows with low MRT may need modifications to the quantity and nature of the simulation—based training that is offered in order to maintain the high level of clinical performance expected in the Angio Suite.

### 8.6.3 Clinical Transfer Potential

Due to the potential severity of clinical errors in cerebral aneurysm coiling, it is difficult to assess the transfer potential of these technical skills in the manner in which they were trained in simulation. However, based on improvements seen in this study and the established validity of this simulator, clinical interventionalist fellows may be able to accelerate their progression towards clinical competence and seniority with a supplemental simulation-based training program.

### 8.6.4 Future Directions

This study focused primarily on simulation-based skills acquisition and testing in novices outside the specialty, and would benefit from further investigation in a clinical setting. Primarily, it is important to identify which of the identified markers of coiling performance can be sensibly assessed in the Angio Suite and whether they can be applied as standardized measures of performance. Translating the skills learned in simulation to the clinical environment would support the value and importance of simulation in this specialty.

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# 9 General Discussion

## 9.1 Impact of Research Directives

The state of training in interventional radiology is at a natural crossroads where, to avoid the interruptive collision of competing training modalities – apprenticeship-style learning in the operating room and independent acquisition of technical skills using high fidelity simulators, we must propose the 'rules of the road' to best convey to the specialty which training modalities and subsequent skillsets provide the highest return on invested time.

We collected data that the attending neurointerventionalist considered the highest frequency of errors to be femoral artery punctures, catheterization of vessels, and overall procedural tasks. One of the main considerations with these answers is that these are earlier stages of the procedure that fellows with lower level of experience get to perform, and carry less risks, therefore are making visible, noticeable errors as a result. A parallel observation is that computer-based task simulators can forego some of these steps in their training curricula, creating training gaps if they were to be formally considered as a supplementary training modality. This is an important reflection since while we grade performance on more specific endovascular maneuvers and establishing 'competency', we may be avoiding a subset of skills which may actually lead to most, albeit small, errors in the Angio Suite.

The highest severity of errors were reported to be catheterization of vessels and aneurysm coiling. Thankfully simulators are already attempting to address these skills through targeting training modules and detailed data. It is paramount that efforts are made within the simulation environment to allocate predictive error statistics as well as guided error management strategies (Boyle et al., 2011; Harris, 2017; Satava, 2005) at these procedural points in order to minimize the potential for training fellows to translate any training scars into the Angio Suite.

This data provided us with an understanding of the subsets of skills that are important for novices to train. Skills with highest importance often also had the highest consequence if they were not done correctly. Skills with the lowest importance also have the highest levels of errors. Finally, highest severity potential also had the lowest frequency. These groupings can shape the way we approach education of skillsets – frequent, low impact errors may be better candidates for technical, competency-based training curricula that may be done independent of the attending physician, and high importance of procedures that carry high potential severity of errors may be better candidates for a joint training modality using repetitive simulation-based skill development and targeted debriefing-based, guided training sessions with experts.

Assessments of core simulation-based performances in our assessments were in agreement with the literature – simulator practice can provide efficient delivery of skills to improve procedural time within the simulation space (Dawson DL et al., 2007; Dayal et al., 2004; Mazzaccaro & Nano, 2012; Patel et al., 2006; a. Spiotta et al., 2011b; Van Herzeele et al., 2008). Fluoroscopy use was also reduced throughout the sessions, in agreement with literature (Dawson DL et al., 2007; Dayal et al., 2004; Mazzaccaro & Nano, 2012; Patel et al., 2006; a. Spiotta et al., 2011b; Van Herzeele et al., 2008; Willaert et al., 2012). Analyzing the trajectory of tool motion in our assessments revealed something more granular – novices practicing on the simulator were reducing the amount of time they spent in incorrect vasculature, improving their overall navigational efficiency. This is an incredibly enlightening result as it was further highlighted in by low mental rotation individuals being particularly impacted by their inability to find the correct vasculature compared to their high mental rotation counterparts. By providing opportunities for novices to improve their visuospatial skills or by facilitating their learning process on the simulator, we can create an equitable training environment that ensures all trainees can hit their potential efficiently.

One of the ways we can do this, as we've seen in our third aim, is by providing an anatomy overlay to low MRT novices. By facilitating their understanding of the vasculature beyond the flat fluoroscopic imaging, we can drastically improve their ability to perform simulated diagnostic angiograms. However, an important point still remains. There are points in the training process where guidance and feedback may be paramount. Some navigational points, such as the bifurcation of the common carotid artery, were tasking enough that repetitive practice under timed conditions were not enough of a learning opportunity to appreciate the 3-dimensional nature of this bifurcation and the translation of that twisting external carotid artery on to a 2-dimensional image. This is an opportunity for us to provide guided feedback or visual cues to help novices, especially those with low MRT, find their way. This is an effect we saw clearly in our third study where an anatomy overlay had the greatest improvement on performance in this group.

Assessing the procedural steps deemed to be of most importance and highest risk by neurointerventionalists in Canada, such as aneurysm access and coiling, we were able to lay the groundwork for the training environment which would be necessary to appropriate train this skillset in a derisked simulation. Novices are able to learn how to navigate the carotid and cerebral vessels, deploy aneurysm coils with increasing success and pack aneurysms to a standard observed by experts in the Angio Suite, however, they need guidance and feedback on the strategies they can employ to prevent aneurysm perforations. This is an important point where we can use scientific data to create clear delineations in where an expert's valuable time is of highest necessity to oversee training.

A constant concern with training conducted solely on a simulator, no matter high validated and/or representative/realistic it is, is its ability to train translatable skills without instilling training scars, overconfidence and unpreparedness for new clinical scenarios. A hybrid model of independent practice, deliberate guidance on simulation, and translational performance metrics is the key to ensuring the neurointerventionalists of tomorrow are prepared and accommodated for the needs of tomorrow.

## 9.2 Clinical Translation

There were opportunities that were unfortunately missed during this research trajectory that may have had a significant impact on the generalizability and applicability of our results. Due to the onset of COVID-19, we were unable to proceed with the originally strategized final objective of assessing expert performance markers in the Angio Suite using video-based workflow analyses. This data would have been fundamental in providing an objective surgical 'signature' that could be applied to and emulated by trainees and fellows on the ANGIO Mentor. Providing bidirectional metrics between the simulation lab and the Angio Suite would create a novel assessment language outside of the standardized rating scales, and push for more translational, objective metric collection within this field.

Clinical translation of skills is the ultimate test of the efficacy of simulation-based training in preparing healthcare professionals for the challenges of clinical practice. It's fundamental role in medical training is supported by the objective of simulation-based training which is not just to teach technical skills but to improve patient safety and outcomes. If medical professionals can effectively apply the skills they have learned through simulation training to real-life patient care, it suggests that the training was successful in preparing them for the challenges of clinical practice. To that extent, we can only make large assumptions about the efficacy of our training modalities until they can be translated and quantified in a clinical setting.

In the reflection of the multitude of skillsets tested in the breadth of this thesis, clinical translation of skills would also identify areas where simulation-based training can be improved. If medical professionals struggle to apply the skills they have learned through simulation training to real-life patient care, it suggests that the training was inadequate in some way.

## 9.3 Future Directions

One of the main limitations of this work is proving the translation and impact of the metrics observed on the simulator on Angio Suite performance. Future studies should make an effort to standardize metrics between the two environments in order to be able to objectively compare performance beyond standard outcomes seen in literature, such as patient outcomes and operating efficiency.

Subsequent work using high fidelity simulators should also attempt to employ finer markers of expert tool use, such as tool rotation, smoothness of tool tip (Belvroy et al., 2020; Estrada et al., 2016), and forces exerted on the aneurysm lumen and arterial wall (Rafii-Tari et al., 2017). This data would provide excellent insight on the ability to fine tune motor skills outside of the operating room, a directive most US surgery program directors support (Haluck et al., 2001).

The promise of these studies advocates for the purposeful implementation of simulation into training curricula (Kreiser et al., 2021), and a concentrated movement towards proficiency rather than exposure. The upcoming neurointerventionalists are already starting their training with new techniques and expectations; we just need to give them the right tools.

## 9.4 Conclusions

The research presented in this body of work underscores the importance of identifying and facilitating independent, autonomous, simulated technical practice in order to supply the experts of tomorrow with the skills they need. Neurointerventionalists should feel reassured that the systems are in place to make appropriate, efficacious use of technology, focused practice methodologies and competency-based training to funnel the fellows towards success.

We can provide equitable training to fellows with different training requirements, such as facilitated learning schemas; create autonomous training paradigms to ensure practice can be focused, measured, and useful; and guarantee wide ranges of case exposure and standardized metrics for performance assessment applicable across the specialty. With these systems in place, simulation can be better incorporated with traditional training paradigms to facilitate continuous training and acquisition of technical skills.

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# Appendices

## Appendix A - Research Ethics Board Approval (2017)

Western Research

Research Ethics

**Western University Health Science Research Ethics Board**
**HSREB Annual Continuing Ethics Approval Notice**

**Date**: March 17, 2017
**Principal Investigator**: Sandrine de Ribaupierre
**Department & Institution**: Schulich School of Medicine and Dentistry\Clinical Neurological Sciences,Western University

**Review Type**: Delegated
**HSREB File Number**: 104787
**Study Title**: Development of objective assessment tools for evaluating clinical performance associated with cerebral angiography and aneurysm coiling.

**HSREB Renewal Due Date & HSREB Expiry Date**:
Renewal Due -2018/03/31
Expiry Date -2018/04/01

The Western University Health Science Research Ethics Board (HSREB) has reviewed the Continuing Ethics Review (CER) Form and is re-issuing approval for the above noted study.

The Western University HSREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use Guideline for Good Clinical Practice (ICH E6 R1), the Ontario Freedom of Information and Protection of Privacy Act (FIPPA, 1990), the Ontario Personal Health Information Protection Act (PHIPA, 2004), Part 4 of the Natural Health Product Regulations, Health Canada Medical Device Regulations and Part C, Division 5, of the Food and Drug Regulations of Health Canada.

Members of the HSREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

# Appendix B - Research Ethics Board Approval (2022)

Western Research

**Date:** 16 December 2022

**To:** Dr. Sandrine de Ribaupierre

**Project ID:** 102917

**Study Title:** Learning with virtual environments

**Application Type:** Continuing Ethics Review (CER) Form

**Review Type:** Delegated

**Date Approval Issued:** 16/Dec/2022 09:58

**REB Approval Expiry Date:** 12/Dec/2023

**Ethics Approval Lapse:** December 13 - 16, 2022*

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Dear Dr. Sandrine de Ribaupierre,

The Western University Non-Medical Research Ethics Board has reviewed this application. This study, including all currently approved documents, has been re-approved until the expiry date noted above.

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University NMREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the Ontario Personal Health Information Protection Act (PHIPA, 2004), and the applicable laws and regulations of Ontario. Members of the NMREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB. The NMREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000941.

Please do not hesitate to contact us if you have any questions.

Sincerely,

The Office of Human Research Ethics

***Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).***

# Curriculum Vitae

**Oleksiy Zaika**

## Education

| | |
|---|---|
| 2023 | **Ph.D.** Anatomy & Cell Biology, Western University |
| 2015 | **M.Sc**. Clinical Anatomy, Western University |
| 2013 | **B.Sc**. Biomedical Sciences, University of Guelph |

## Employment

| | |
|---|---|
| 2022 - Present | **Co-Founder**, Vessl Prosthetics Inc., London, Ontario |
| 2021 - Present | **Fellow**, Medical Innovation Fellowship – WorlDiscoveries, Western University |
| 2013 - 2020 | **Teaching Assistant**, Anatomy & Cell Biology, Western University |
| 2018 - 2019 | **Instructor**, Anatomy of the Human Body, Western University |
| 2014 | **Instructor**, Brain and Behaviour, Algoma University |

## Awards and Honours

| | |
|---|---|
| 2020 | **Invited Judge**, Technology Consulting Competition, Ivey Fintech |
| 2018, 2019 | **Teaching Excellence Recognition**, School of Health Studies, Western University |
| 2019 | **Invited Panelist**, Alumni Society, Western University |
| 2019 | **Invited Moderator**, London Health Research Day |
| 2018 | **Best Conference Oral Presentation**, Society in Europe for Simulation Applied to Medicine |
| 2018 | **Invited Panelist**, TA Training Day, Western University |
| 2015 - 2018 | **AAA Student Travel Scholarship**, American Association of Anatomists |
| 2017 | **Oral Presentation Finalist**, American Association of Anatomists |
| 2017 | **Anatomy & Cell Biology Travel Award**, University of Western Ontario |
| 2013 | **Student Last Lecturer** for the Graduating Class of 2013, University of Guelph |

## Fellowships and Scholarships

| | |
|---|---|
| 2023 | **Winner**, Synapse Life Sciences Competition, $55,000 |
| 2023 | **Accepted**, Mitacs e-Accelerate Grant, $60,000/year |
| 2022 | **Recipient**, Intellectual Property Ontario – Med-tech Grant, $25,000 |
| 2022 | **Recipient**, Medical Innovation Xchange, Knowledge Transfer Grant, $15,000 |
| 2022 | **Recipient**, Mitacs International, $5,000 |
| 2022 | **Recipient**, AC Studio Ventures, $20,000 |
| 2022 | **Winner**, MSK Innovation Competition, Bone and Joint Institute, $25,000 |
| 2021 | **Finalist**, Synapse Life Sciences Competition, $5,000 |
| 2017 - 2020 | **Frederick Banting and Charles Best Canada Graduate Scholarship (CGS-D),** Canadian Institutes of Health Research, $35,000/yr |
| 2016 | **Ontario Graduate Scholarship**, Ministry of Advanced Education and Skills Development, $15,000 |

## Leadership

| | |
|---|---|
| 2021 – 2022 | **President**, University Consulting Group, Western Chapter |
| 2019 – 2021 | **Co-Founder** and VP Strategy, University Consulting Group, Western Chapter |
| 2018 | **Mentor**, Microteaching in Anatomy, Western University |
| 2016 – 2018 | **Co-Chair**, ACB Graduate Student Council, Western University |
| 2016 | **Bike Mechanic**, Purple Bikes, Western University |
| 2015 – 2016 | **Councillor**, Society of Graduate Students, Western University |
| 2015 – 2016 | **Problem-Based Learning Facilitator**, Clinical Anatomy Graduate Program, Western University |

## Research Contributions

### Manuscripts

**Zaika, O.,** Boulton, M., Eagleson, R., & de Ribaupierre, S. (Submitted). Visuospatial Assistance in Simulation-based Cerebral Angiography Training. Clinical Neuroradiology

**Zaika, O.,** Boulton, M., Eagleson, R., & de Ribaupierre, S. (In-Peer-Review). Perceived Significance of Clinical Steps and Frequency of Errors in Cerebral Aneurysm Coiling. World Neurosurgery

**Zaika, O.,** Boulton, M., Eagleson, R., & de Ribaupierre, S. (2023). Development of Technical Skills in Simulated Cerebral Aneurysm Coiling. Medicine.

**Zaika, O.,** Boulton, M., Eagleson, R., & de Ribaupierre, S. (2020). Simulation reduces navigational errors in cerebral angiography training. Advances in Simulation, 5(1), 1-8.

**Zaika, O.,** Nguyen, N., Boulton, M., Eagleson, R., de Ribaupierre, S. (2016). Evaluation of User Performance in Simulation-Based Diagnostic Cerebral Angiography Training. In MMVR

Mitchnick, K., Creighton, S., Cloke, J., Wolter, M., **Zaika, O.**, Christen, B., Van Tiggelen, M., Kalisch, B., Winters, B. (2016). Dissociable roles for histone acetyltransferase p300 and PCAF in hippocampus and perirhinal cortex-mediated object memory. Genes, Brain & Behaviour

### Podium Presentations

**Zaika, O.,** Boulton, M., Eagleson, R., de Ribaupierre, S. (2019). Aneurysm Coiling and Simulation – Assessing Risks and Skills in Clinical Proficiency. Invited to speak at the 2018 SESAM (The Society in Europe for Simulation Applied to Medicine) conference, Glasgow, Scotland.

**Zaika, O.,** Boulton, M., Eagleson, R., de Ribaupierre, S. (2018). Simulation-Based Cerebral Angiography Coiling Training Performance in Novices. Invited to speak at the Best Abstracts session of the 2018 SESAM (The Society in Europe for Simulation Applied to Medicine) conference, Bilbao, Spain.

**Zaika, O**., Boulton, M., Eagleson, R., de Ribaupierre, S. (2018). Simulation-Based Cerebral Angiography Coiling Training Performance in Novices. Invited to speak at the 2018 SESAM (The Society in Europe for Simulation Applied to Medicine) conference, Bilbao, Spain.

**Zaika, O.,** Boulton, M., Eagleson, R., de Ribaupierre, S. (2018). Cerebral Aneurysmal Coiling in Virtual Reality - An Overview of Novice Skill Development. Invited to speak at the 2018 American Association of Anatomists conference, San Diego, CA, USA.

**Zaika, O.,** Boulton, M., Eagleson, R., de Ribaupierre, S. (2017). Effect of Simulation-Based Cerebral Angiography Training on Navigational Error in Novices. Invited to speak at the 2017 American Association of Anatomists conference, Chicago, IL, USA.

**Zaika, O**., Nguyen, N., Boulton, M., Eagleson, R., de Ribaupierre, S. (2015). Evaluating simulator performance in diagnostic cerebral angiography. Presented at the 2015 CNS Departmental Research Day conference, London, ON.

## International Abstracts

**Zaika, O**., Boulton, M., Eagleson, R., de Ribaupierre, S. (2019). Understanding Aneurysm Coiling in Practice: A Delphi Inquiry into Expert Perception. Experimental Biology 2017, Orlando, FL, USA

**Zaika, O**., Boulton, M., Eagleson, R., de Ribaupierre, S., (2018). Novice Development of Cerebral Aneurysm Coiling Skills in Virtual Reality. Association for Medical Educatio in Europe (AMEE) 2018, Basel, Switzerland

**Zaika, O**., Boulton, M., Eagleson, R., de Ribaupierre, S. (2017). Effect of Simulation-Based Cerebral Angiography Training on Navigational Error in Novices. Experimental Biology 2017, Chicago, IL, USA

**Zaika, O**., Boulton, M., Eagleson, R., de Ribaupierre, S., (2016). Self-Guided Error Reduction in Simulated Diagnostic Cerebral Angiography. Simulation Summit, Royal College of Physicians and Surgeons of Canada, St. John's, Canada

**Zaika, O.,** Nguyen, N., Boulton, M., Eagleson, R., de Ribaupierre, S., (2016). Assessing simulation-based interventional angiography training in novices. Experimental Biology 2016, San Diego, USA

**Zaika, O**., Nguyen, N., Boulton, M., Eagleson, R., de Ribaupierre, S., (2015). Effectiveness of Simulated Aneurysm Diagnosis & Coiling in Cerebral Angiography. AMEE 2015, Glasgow, Scotland

**Zaika, O.,** Nguyen, N., Boulton, M., Eagleson, R., & de Ribaupierre, S. (2015). Effectiveness of Simulation-Based Training in Aneurysm Diagnosis & Coiling in Cerebral Angiography. The FASEB Journal, 29(1 Supplement), 691-14.

## Professional Development

| | |
|---|---|
| 2022 | **Velocity Incubator**, University of Waterloo |
| 2022 | **BioNext Incubator**, Robarts Research Insititute |
| 2022 | **Investment Readiness**, Haltech |
| 2021 | **Entrepreneurship for Healthcare Startups**, UCSF Innovation Ventures |
| 2021 | **IP Strategy Boot Camp**, WorlDiscoveries |
| 2021 | **Medical Innovation Bootcamp**, WorlDiscoveries |
| 2020 | **Fundamentals of Business Analysis**, Algonquin College |
| 2020 | **Master the Entrepreneur Skillset**, Ivey Business School |
| 2019 | **New Venture Creation**, SGPS, Western University |
| 2019 | **Propel**, Western University |