ULTRASOUND RELIABILITY OF BLOOD FLOW MEASUREMENTS IN NECK VASCULATURE: A COMPARISON BETWEEN A NOVICE AND EXPERIENCED SONOGRAPHER

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Abstract

Current literature on the reliability of ultrasound in measuring blood flow volume of the neck vasculature remains sparse, especially when comparing the reliability of these measurements taken by a novice sonographer to an experienced sonographer. This study sought to examine the reliability of blood flow measurements taken by a novice and experienced sonographer in the left common carotid artery (CCA), internal carotid artery (ICA), and vertebral artery (VA) using duplex Doppler ultrasound (DDU). Intraclass correlation coefficients (ICCs) revealed poor inter-rater reliability within the CCA (-.127 to .445) and ICA (.066 to .321), and moderate reliability in the VA (.694 to .725). ICCs also revealed moderate intra-rater reliability of novice blood flow measurements in the CCA (.701) and ICA (.729), and good reliability in the VA (.818). Results demonstrated an overall lack of inter-rater reliability, suggesting a single sonographer be used for research involving repeated evaluations to increase consistency in measures.

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List of Abbreviations

Abbreviation	**Expanded Word**
U/S	Ultrasound
DDU	Duplex Doppler ultrasound
CCA	Common carotid artery
ICA	Internal carotid artery
VA	Vertebral artery
MRI	Magnetic resonance imaging
PC-MRI	Phase contrast magnetic resonance imaging
ASL	Arterial spin labelling
SCAT6	Sport Concussion Assessment Tool 6
TAMEAN	Time-averaged mean velocity
BFV	Blood flow volume
ICC	Intraclass correlation coefficient
WHIPR	Whiplash and Head Injury Prevention and Rehabilitation

Chapter 1: Introduction and Literature Review

Introduction

As defined by the American Association of Neurosurgeons (AANS), a concussion is a brain injury resulting in temporary loss of normal brain function,[1] typically lasting up to 14 days.[2,3] In relation to sport and exercise, the most recent Concussion in Sport Group (CISG) consensus statement defines concussion as a traumatic brain injury caused by a direct blow to the head, neck, or body during sport and exercise-related activities.[4] Between 2002 and 2016, over one fifth of injury related deaths in Canada were associated with a diagnosis of traumatic brain injury.[5] During 2019, concussion, a mild form of traumatic brain injury, was reported to be experienced one or more times by 1.6% of Canadians aged 12 and over.[6] Research into concussion assessment has found that concussed athletes demonstrate significantly less cerebral blood flow eight days after concussion compared to twenty-four hours within concussion.[7] Furthermore, studies have shown that males with history of concussion show lower cerebral blood flow bilaterally compared to males without history of concussion, while females with multiple concussions have lower cerebral blood flow posteriorly compared to females with a single concussion.[8] These changes in cerebral blood flow are currently assessed using a technique known as Magnetic Resonance Imaging (MRI). Since evidence suggests cerebral blood flow is reduced by concussion, this raises the question of whether the same relationship can be found in the blood vessels supplying the brain in individuals who have incurred a concussion. The blood vessels that supply the brain are the carotid and vertebral arteries and ascend to the head in the neck (Figure 1). If the same relationship is found, techniques such as Doppler ultrasound could be used clinically on these arteries to help monitor concussion recovery. From a research standpoint, exploring this relationship will help further understand the potential physiological changes associated with concussion. Current assessment of blood flow in the carotid and vertebral arteries are performed using techniques such as MRI, as well as ultrasound (U/S).

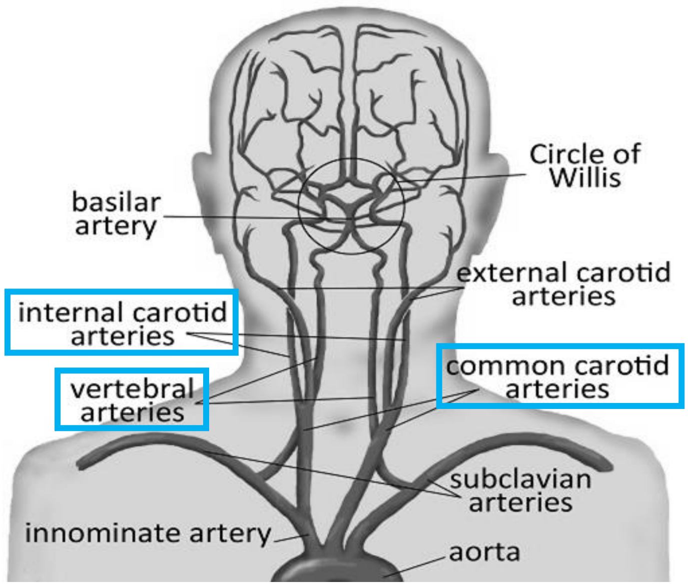

Figure 1. *Common carotid, internal carotid, and vertebral arteries in relation to the major vasculature of the head, neck, and brain. The highlighted vessels supply blood to the brain and are the arteries of interest in this study.*[9]

Research in the field of ultrasound reliability reveals inconsistent findings, as ultrasound has been shown to possess varying levels of inter and intra-rater reliability. Another factor contributing to this inconsistency is the overall sparsity of research on the efficacy of ultrasound transducer holders. Furthermore, not all ultrasound reliability studies have measured blood flow and instead have measured reliability of parameters such as muscle morphology,[10] making this specific field of research especially sparse. Of the few reliability studies that have measured blood flow, many have assessed vessels apart from the common carotid, internal carotid, and vertebral arteries such as the vasculature in the leg[11] and diaphragm.[12] The limited amount of research in this area contributes to a major gap in knowledge. This will be addressed in this thesis by exploring the inter-rater and intra-rater reliability of duplex Doppler ultrasound (DDU) in assessing blood flow of the common carotid, internal carotid, and vertebral arteries when evaluated by both a novice and experienced sonographer.

Literature Review

Magnetic resonance imaging

Magnetic resonance imaging (MRI) is a commonly considered non-invasive form of diagnostic imaging used to produce detailed images of the body's internal anatomy. This includes organs, muscles, bones, and blood vessels.[13] MRI produces images using magnets, as the magnetic environment of MRI causes protons in the body to realign. Radio waves emitted by MRI cause these protons to emit signals which are then used to develop cross-sectional MRI images.[14] When assessing blood flow using MRI, arterial spin labelling (ASL) and phase-contrast magnetic resonance imaging (PC-MRI) are commonly used. ASL is an MRI technique in which arterial blood water is magnetically tagged to determine the velocity at which blood is travelling.[15] PC-MRI quantifies blood velocity using velocity encoded phase shifts, which allow for the measurement of blood flow.[16] Despite its ability to produce detailed images, MRI is associated with several known risks. Due to the magnetic field associated with MRI, magnetizable objects within this field become projectiles. This means individuals with any implant involving magnetized metal, such as older pacemakers, cannot undergo MRI scan. Additionally, due to its loud nature, MRI may be unbearable for those experiencing over-sensitivity to sound due to concussion or another auditory dysfunction. Furthermore, MRI may not be tolerable to those with claustrophobia and can cause twitching. In rare cases, contrast agents used during MRI may result in health complications, including entering the blood stream of a fetus in pregnant women.[17] Finally, MRI is cost-intensive and a major contributor to the overall costs of healthcare.[18] Regardless of its risks and disadvantages, studies have previously found MRI to be accurate in quantifying blood flow.[19]

Ultrasound

Another form of diagnostic imaging, known as Ultrasound, is a commonly considered non-invasive technique used to create images within the body. Ultrasound works using high frequency sound waves known as ultrasound waves. These waves are emitted by a transducer and travel until they contact structures within the body. These waves then reflect to the transducer where an electrical signal is generated, allowing for the ultrasound machine to create an image known as a sonogram.[20] There are three main types of ultrasound transducers, each of which serve a different purpose. They are named as follows: Linear probe, Curvilinear probe, Phased Array probe. Linear array probes are ideal for imaging close to the body's surface, while curvilinear probes are ideal for imaging deeper in the body. Phased array probes are ideal when imaging in smaller areas, such as the brain and heart.[21, 22] Within the context of assessing blood flow, an imaging procedure known as duplex Doppler ultrasound (DDU) is used. This combines traditional Doppler ultrasound which detects the movement of blood, with b-mode ultrasound which produces images of blood vessels.[23] This allows for the visualization of blood flow through structures such as organs and blood vessels. This includes the common carotid, internal carotid, and vertebral arteries, which are the vessels of interest in this study. Assessing blood flow within these vessels involves the use of a linear array probe due to their relatively superficial location in the neck. DDU imaging allows sonographers to determine blood flow velocity and the direction of blood flow; this form of imaging can be used as an alternative to PC-MRI when assessing blood flow.[24] Through its ability to create images using high frequency waves, Doppler ultrasound is used for a variety of purposes including identifying potential blood vessel damage or blockage, as well as monitoring blood flow post-surgery.[25]

Compared to MRI, there are many instances in which ultrasound is not the favorable imaging technique. For example, the attenuation of ultrasound waves can compromise image quality with increasing levels of adiposity. This weaker signal results in images with less clarity.[26] Additionally, ultrasound is ineffective in producing images in areas of the body containing gas including the lungs, or in areas covered by bone.[27] Furthermore, the validity of ultrasound imaging is highly dependent on the sonographer, with studies demonstrating that even experienced sonographers can find variability between their results. In a study involving fifteen vascular scientists from England, each scientist measured the peak systolic and end diastolic volume of the common carotid and internal carotid arteries in a single subject. It was found that 9% of all images were clinically determined as suboptimal due to factors such as suboptimal angle correction and suboptimal angle of insonation.[28] The ability for experienced vascular scientists to make errors when using ultrasound indicates the likeliness for sonographers with a lack of experience to incur similar or even greater amounts of errors.

As previously mentioned, MRI is an accurate measure in quantifying blood flow, however ultrasound may be preferred due to its limited risk and high accessibility. There are no known risks or side effects of ultrasound scans[29] in contrast to MRI, which possesses multiple risk factors. Furthermore, ultrasound is considered more accessible as it is available to a broader range of patients, such as people who are pregnant or those with magnetized metal implants.[30,31]

Not only is ultrasound more affordable than MRI,[32] but ultrasound has the capacity to be portable and therefore can be brought bedside for assessment.

Doppler shift frequency

Assessing blood flow using Doppler ultrasound is made possible through the Doppler effect, which states that waves emitted by an object travelling toward an observer are of higher frequency, whereas waves travelling away from an observer are of lower frequency.[33] With respect to blood flow, the frequency of the signal transmitted by the transducer will change when it is reflected by red blood cells, and this change is proportional to the velocity of the red blood cells. This change is known as Doppler frequency shift or Doppler shifted signal, which is illustrated in Figure 2. Doppler frequency shift can be calculated using the following formula:

$$\Delta F = Ft - Fr = \frac{2Ft\ v\ cos\theta}{c}$$

Within this formula, ΔF represents Doppler frequency shift or Doppler shifted signal, Ft represents the transmitted frequency, Fr represents the received frequency, v represents the velocity of blood flow, θ represents the angle between the direction of the ultrasound beam and direction of blood flow, and c represents the speed of sound waves through tissue (1540m/s).[34, 35] In combination with its cross-sectional area, measuring the velocity of blood flow in a vessel allows for the determination of blood flow volume.

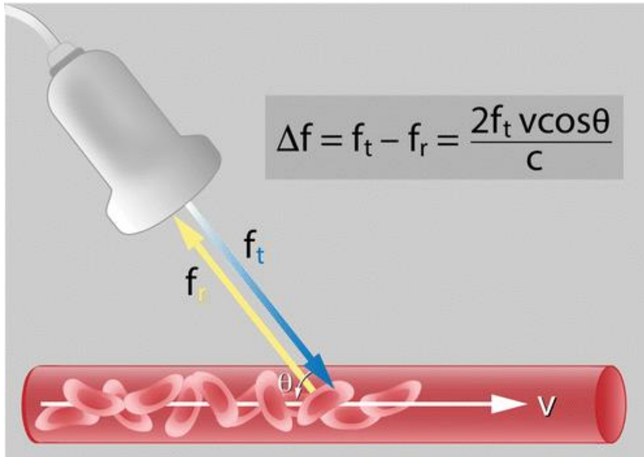

Figure 2. *Visualization of Doppler frequency shift*.[34]

Angle of insonation

As mentioned previously, the variable θ in the Doppler frequency shift equation denotes the angle between the direction of the ultrasound beam and direction of blood flow. This relationship is known as the angle of insonation. If the transducer is parallel to the direction of blood flow, then the angle of insonation is 0 degrees. This would yield the highest Doppler shifted signal as cos (0°) = 1. Conversely, if the transducer is perpendicular to the direction of blood flow, this angle is 90 degrees. As seen in Figure 3, this angle would yield no Doppler signal as cos (90°) = 0. A 0-degree angle of insonation is not feasible, and a 90-degree angle does not generate any Doppler shifted signal, meaning neither of these insonation angles are effective when measuring blood flow using DDU.

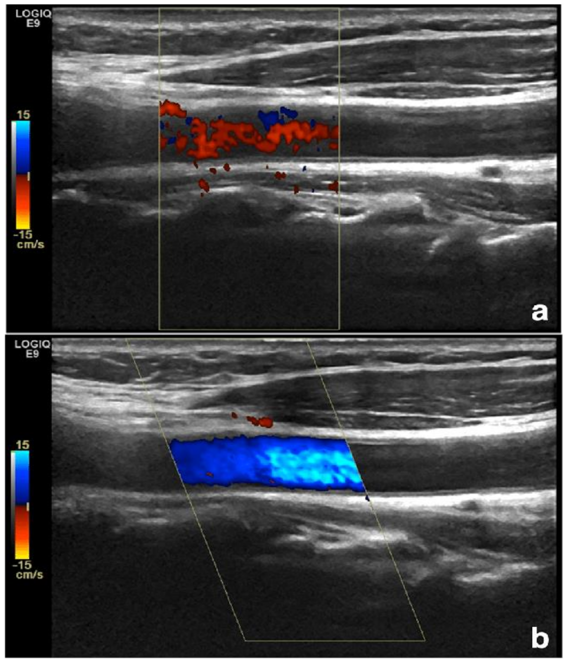

Figure 3. *Demonstration of how an angle of insonation of 90 degrees (a) yields no detectable blood flow when compared to a corrected angle of insonation (b).*[36]

It is noted that an angle of 60 degrees or less should be used, as angles between 60 and 90 degrees cause the cosine of the angle of insonation to drastically change. This means small errors in angles above 60 degrees will result in a drastic overestimation of velocity.[37] This advice, however, is quite broad as the literature does not suggest a single angle, but rather an angle between 30 and 60 degrees.[38] This is especially concerning as studies have found varying results when using different angles of insonation less than or equal to 60 degrees. In a study comparing the determinability of internal carotid stenosis at two different angles of insonation, it was found that peak systolic and end diastolic velocities obtained at a 60-degree insonation angle were respectively 24.2% and 24.7% higher than those obtained at a 45-degree angle.[39] This acts as a point of concern as the use of varying angles of insonation may alter the accuracy of measurements. This is not only applicable to stenosis, but vascular ultrasound imaging in general. From the perspective of a reliability study, although different angles of insonation will likely yield different results, what is most important is that all measurements are made using the same angle of insonation. This will ensure consistency across all measurements.

Reliability and Validity

Reliability and Validity are both metrics that can be calculated in quantitative research. Reliability is defined as the extent to which measurements yield the same result on repeated trials.[40] In this study, inter-rater and intra-rater reliability were measured by calculating intraclass correlation coefficients (ICCs) and can be categorized as seen in table 1. Inter-rater reliability measures the variation between two or more raters who measure the same group of subjects, whereas intra-rater reliability measures the variation of data measured by one rater across two or more trials.[41] Validity can be defined as the extent to which a concept is accurately measured.[42] Within the context of this study, which compares the reliability of blood flow volume (BFV) measurements obtained by a novice and experienced sonographer, greater inter-rater reliability indicates greater agreement between the measurements obtained by both sonographers. In other words, the greater the inter-rater reliability is, the more similar the novice's collected BFV measurements are to those collected by the experienced sonographer. Since it is expected for an experienced sonographer to obtain accurate BFV measurements, by assessing inter-rater reliability, this also serves to assess the overall accuracy of the novice sonographer's measurements. Hence, agreement between the novice and experienced sonographer would imply the novice can obtain accurate BFV measurements. In summary, greater inter-rater reliability found in this study would translate to greater accuracy of the novice's BFV measurements.

Table 1. *Categorization of various Intraclass correlation coefficients (ICCs).*[43]

ICC Value	Reliability Categorization
<0.5	Poor
0.5 – 0.75	Moderate
0.75 – 0.9	Good
>0.9	Excellent

Intra and Inter-rater reliability of Ultrasound

Within the literature, few studies exist that examine the intra-rater and inter-rater reliability of ultrasound in specifically assessing blood flow metrics in the common carotid, internal carotid, and/or vertebral arteries.[44-46] Of the studies that have been conducted, results have been inconsistent. This can be observed in the following studies.

Johnson et al.[44] measured the reliability of colour duplex Doppler ultrasound in measuring vertebral artery blood flow and velocity. With respect to vertebrobasilar insufficiency, ten asymptomatic subjects with a mean age of 33 years participated in this study. It was found that the intra-rater reliability of peak blood flow velocity measurements varied based on the location of the vertebral artery that was measured. At the level of cervical vertebrae 1 and 2 (C1-2), peak velocity reliability was poor when a single measurement was taken (ICC = 0.26) whereas reliability was fair when three measures were taken (ICC = 0.77) and good when five measurements were taken (ICC = 0.83-0.84). At the level of C2-3, peak velocity reliability was poor regardless of how many measurements were taken (ICC = 0.37-0.63). In assessing mean velocity, poor reliability was found in C2-3 when taking a single measurement (ICC = 0.39), fair reliability was found when the first three measurements were averaged (ICC = 0.73), and good to high reliability was found when five measurements were sampled (ICC = 0.88-0.91). At C5-6, good reliability was found when measuring volume flow rate using a single measurement, as well as using the means of three or five measurements (ICC = 0.81-0.86).[44] The results of this study concluded that the reliability of blood flow was influenced by the location at which measurements were taken, as well as the number of measurements used to determine reliability, with multiple measurements being deemed more optimal than a single measurement.

Similarly, findings in the reliability of Doppler ultrasound in measuring peak systolic velocity in the internal carotid artery found poor results.[45] In this study, thirty-one patients underwent ultrasound by three vascular technologists. Participants involved were suspected to have carotid artery occlusive disease, had existing stenosis, or were partaking in post-operative surveillance. It was found that when peak systolic velocity was measured as a categorical variable (categorization of peak systolic volume into <50% stenosis, 50%-70% stenosis, >70% stenosis), inter-rater agreement was high, but when measured as a continuous variable (no categorization), agreement between technologists was as low as -27% and as high as 43%.[45] Overall, when considering the reliability of peak systolic velocity when measured as a continuous variable, reliability was poor across all three raters, suggesting ultrasound may not be suitable in reliably assessing this measure.

As opposed to assessing blood flow in only one artery, Schöning et al.[46] assessed the repeatability of blood flow measures in the common carotid, internal carotid, external carotid, and vertebral arteries. This study involved forty-eight participants with no history or signs of cerebrovascular disease (25 men and 23 women, mean age 35 years ± 12) and measured vessel diameter, average velocity, flow volumes, as well as peak systolic, end diastolic, and time averaged maximum velocities in addition to resistance, pulsatility, and spectral broadening indexes. One year after initial measurements, a reproducibility study was completed by the same examiner on twenty-two of the participants (13 men and 9 women, mean age 33 years). It was found that the long-term reproducibility of cerebral blood flow and flow volumes in all vessels was significant.[46] Despite the findings, this study was performed in 1994, and no study has been found since to validate these findings. Furthermore, the reproducibility study did not involve all original participants, potentially impacting results. This study provides some support for the capability of ultrasound in producing repeatable measures when used by the same sonographer.

Apart from assessing blood flow, ultrasound has also been tested in its reliability in assessing measures such as the quantification of muscles. A review by Nijholt et al.[47] examined the intra and inter-rater reliability of ultrasound across 13 studies in quantifying muscles in adults ≥60 years. It was found that across all studies, intra-rater reliability estimates ranged from an intraclass correlation coefficient (ICC) of -0.26 to 1.00. Although an ICC of -0.26 seems alarming, this came from a single study that measured eight different muscles, and the range of ICCs within this single study was found to be -0.26 to 0.95. Compared to the other studies in the review, the second lowest ICC was found to be 0.77, while ICCs for most studies were reported to be ≥0.9, with an ICC range of 0.95 to 1.00 being found when assessing absolute muscle thickness of the Transversus abdominis, internal oblique, and external oblique.[48] This indicates that apart from the single poor reliability measure of -0.26, intra-rater reliability was high for all other studies. Additionally, the inter-rater reliability estimates ranged from 0.88 to 0.988.[47] These ICC values support the idea of ultrasound being a reliable method of measurement for muscles.

Overall, the results of the available studies demonstrate that the reliability of ultrasound varies depending on the blood vessel being measured as well as the sonographer. Despite the varying results, the sheer lack of literature in this field of research provides reason to further explore ultrasound reliability in the common carotid, internal carotid, and vertebral arteries.

Ultrasound Transducer Holder

Given the inconsistency of results with respect to ultrasound reliability, the use of a transducer holder may in fact improve the reliability of ultrasound measurements. Very few studies have been conducted to test this claim, thus highlighting the importance for such studies to take place. As of now, no reliability studies were found that involved the use of an ultrasound transducer holder in the assessment of the common carotid, internal carotid, and vertebral arteries. This comes as little surprise as research on ultrasound reliability of these vessels is already sparse, without accounting for the use of a transducer holder. While the use of a transducer holder was not the focus of this thesis, ultrasound transducer holders can provide potential advantages when performing ultrasound. One potential advantage is the minimization of motion artifact. Motion artifact refers to anomalies in ultrasound images caused by involuntary movements of the ultrasound transducer, resulting in visual noise on the ultrasound image. A transducer holder designed by Mahapatra et al., reduced motion artifact in the collected images on a human forearm.[49] Studies involving flow mediated dilation (FMD) have also demonstrated excellent inter-rater and intra-rater reliability when using a transducer holder, with brachial FMD yielding intra-rater and inter-rater intraclass coefficients (ICC) of >0.90 for all measures (artery diameter, %FMD, ΔFMD) except for inter-rater ΔFMD, which had an ICC of 0.89.[50] Given that FMD measures a change in arterial diameter, this study does not directly demonstrate an increase in reliability when measuring blood flow, however it does highlight the potential advantages of using a transducer holder.

In 2008, the incidence of musculoskeletal injuries among North American sonographers was 90%.[51] In the United States, data was collected from approximately 1000 sonographers and found that 84% suffered from ultrasound related pain, with the neck, shoulder, wrist, hands, fingers, and back being most affected.[52] Transducer holders are designed to reduce the amount of effort required to use the ultrasound transducer as they can hold the transducer in place. This reduces the need for sonographers to carry the weight of the transducer while taking images, helping to decrease the risk of ultrasound related pain and/or musculoskeletal injury.

Research Objectives and Hypotheses

The objective of this study was to assess the inter-rater and intra-rater reliability of blood flow measurements of the left common carotid, internal carotid, and vertebral artery, using duplex Doppler ultrasound on a healthy university aged population. This study specifically sought to examine the differences in the reliability of these measures when taken by a novice compared to an experienced sonographer. Current literature on the reliability of ultrasound in the CCA, ICA, and VA is sparse. Of the studies that have been conducted, some support has been shown for the capability of ultrasound in producing repeatable measures. For this reason, it is hypothesized that across all three blood vessels, blood flow volume measurements will demonstrate a minimum of moderate inter-rater reliability (ICC 0.5-0.75) between the novice and experienced sonographer. Furthermore, it is hypothesized that the blood flow volume measurements obtained by the novice sonographer will demonstrate a minimum of moderate intra-rater reliability across all three blood vessels.

Chapter 2: Methods

This study was conducted on a presumably healthy university aged population (18 to 30 years old) with 38 participants being recruited. This sample size falls within that of the studies mentioned in chapter 1. Participants were excluded if they had not been cleared from a recent concussion injury at the time of the study.

Two researchers with varying levels of sonography experience performed the measurements for this study. At the time of the study, one researcher was categorized as a novice (one month of experience) while the other was considered experienced (five years of experience). The experienced sonographer had five years of prior ultrasound experience imaging the carotid and vertebral arteries. This included hands on imaging training from a certified sonographer with over thirty years experience in the industry, as well as repeated scanning from their own research study in addition to using U/S for various other projects. This researcher also attended training at the Okanagan Cardiovascular Ultrasound Summer School at the University of British Columbia Okanagan Campus. The novice sonographer was trained for one month by the experienced sonographer. Training involved reviewing instructional videos created by the experienced sonographer, reviewing literature relevant to the fundamentals of U/S imaging in the carotid and vertebral arteries, performing imaging of these arteries on volunteers, as well as performing a pilot study prior to data collection.

Participants were instructed to lie supine on a treatment table and DDU was used to record blood flow in the left Common Carotid (CCA), Internal Carotid (ICA), and Vertebral (VA) arteries for twenty seconds each.

There were three series of blood flow measurements, and the order in which the raters performed these series was randomized. Two series were completed by the novice and one series was completed by the novice sonographer. For the sake of clarity in this paper, the two series completed by the novice are denoted as series 1 and 2, and the singular series completed by the experienced sonographer is denoted as series 3. Within each of the three series, three blood flow volume measurements were collected for each of the CCA, ICA, and VA. Block randomization was used to assign the order in which these vessels were recorded within each of the series. In addition, both sonographers were blinded to each others' blood flow measurements.

Participants

This study was conducted on a healthy university aged population recruited at York University's Keele campus during the Fall/Winter 2023/2024 school year. Participants were recruited through the Kinesiology Undergraduate Research Experience (KURE) system, allowing for undergraduate students enrolled in the course KINE 2049: Research Methods in Kinesiology to participate in various studies at York University. Participants who took part in the study received a 3% course credit towards their grade in KINE 2049. To have partaken in the study, participants must have met the following inclusion criteria: (a) aged between 18 and 30 years old; (b) have no outstanding concussion injury at the time of the study. Participants with a history of concussion were permitted to participate so long as they were cleared to return to daily activities at the time of the study. Given that the nature of this study was to test reliability, participants were not divided into groups. This study received approval from the Human Participants Review Sub-Committee at York University.

Data Collection

This study took place in the Whiplash and Head Injury Prevention and Rehabilitation (WHIPR) Lab located in Stong College room 115 at York University, and involved one visit which took participants approximately 160 minutes to complete.

Prior to participating in the study, participants were instructed to read and review the informed consent form pertaining to the study. To participate, this form required participants' signatures. At this time, participants were able to ask any questions related to the study.

Participants were then asked to complete three questionnaires/assessments in the following order: Sport Concussion Assessment Tool (SCAT6), Neck Disability Index (NDI) questionnaire, Lab Health & Demographic Questionnaire. The SCAT6 was administered by the novice researcher who was previously trained in administering this assessment, whereas the NDI and Lab Health & Demographic Questionnaires were completed by participants on their own. Participants were required to rest for 15 minutes prior to data collection, in which the completion of the assessments/questionnaires counted towards the 15-minute rest period. Step 4 of the SCAT6: Coordination and Balance Examination, was the only component out of all three assessments that required participants to complete any kind of physical activity. To ensure the 15-minute rest period was properly honored, this step of the SCAT6 was completed first, followed by steps 1 to 3 and step 5.[53]

Upon completion of all questionnaires/assessments, participants were instructed to lie down supine on a treatment table. Using a General Electric (GE) Logiq E Ultrasound machine, DDU was used to record blood flow velocity of the left Common Carotid (CCA), Internal Carotid (ICA), and Vertebral (VA) arteries, with each recording lasting 20 seconds. in twenty second increments. This was done using a 4-12mHz linear array transducer. The left arteries were chosen for the purpose of this study as the left common carotid artery directly branches from the aortic arch, as opposed to the right common carotid artery which branches from the brachiocephalic artery.[54] For the sake of consistency across all measures, an angle correction of 60 degrees was used for each recording.

During the duration of the 20-second recordings, the ultrasound unit measured time-averaged mean blood flow velocities (TAMEAN). Time averaged-mean velocity refers to the mean velocity over a cardiac cycle, which was required for the overall calculation of blood flow. Three series of recordings occurred for each participant, two of which were completed by the novice rater and one by the experienced rater. As noted previously, for the sake of this paper series 1 and 2 correspond to the two series of measurements taken by the novice sonographer, while series 3 refers to the single series of measurements taken by the experienced sonographer (Figure 4).

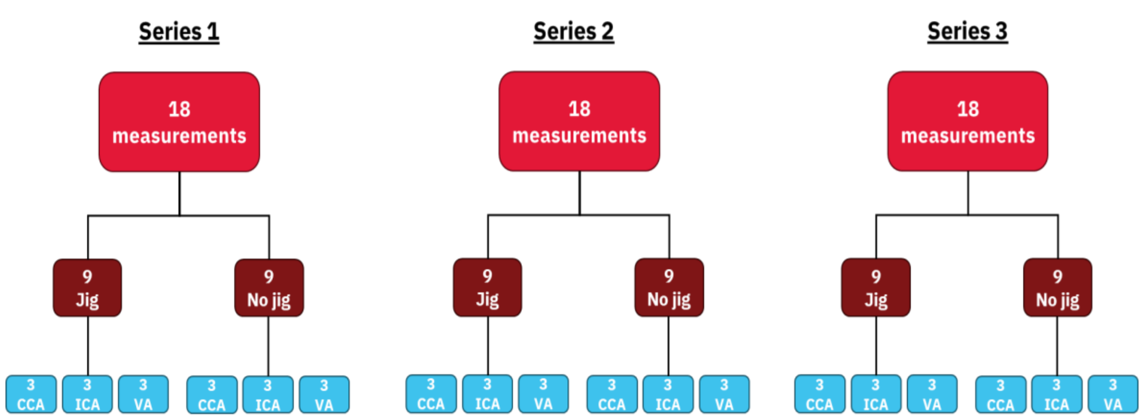

Figure 4. *Schematic demonstrating the measurements that were taken. Two series were completed by the novice sonographer, and one series was completed by the experienced sonographer. Within each series, 18 measurements were taken, nine of which were taken using*

the jig and nine without the jig. Under both conditions, three measurements each were taken of the left common carotid artery (CCA), internal carotid artery (ICA), and vertebral artery (VA).

The order in which the raters performed these series was randomized. This thesis was part of a larger data collection that involved the use of a 3D printed transducer holder or “jig”. Within each series, eighteen recordings were taken: nine recordings using the 3D printed jig (Figure 5), and nine recordings without the use of the 3D printed jig. The order in which the jig was used (i.e., before or after taking recordings without the jig) was also randomized. With and without the jig, three repeated recordings were taken of the left Common Carotid artery (CCA), as well as three repeated recordings of the left Internal Carotid (ICA) and Vertebral (VA) arteries. Each recording was 20 seconds in duration. The order in which these vessels were recorded was randomized as well. Each vessel was located by following the directions outlined by Thomas et al.[38]

Figure 5. *Ultrasound transducer housed by transducer holder / jig.*

Upon recording each vessel for 20 seconds, three randomly selected cardiac cycles from each recording were used to determine a mean velocity and mean vessel diameter value. To calculate a single mean velocity value, the time-averaged mean velocity from each of the three cardiac cycles was averaged to generate a single mean velocity value. To calculate a single mean vessel diameter value, the diameter of the vessel from each of the three cardiac cycles was manually measured and then averaged to generate a single mean diameter value, as shown in Figure 6. To ensure consistency across both sonographers, both sonographers measured vessel diameters by capturing the size of the vessel lumen and were instructed to place the cursor in the center of each blood vessel when recording TAMEAN.

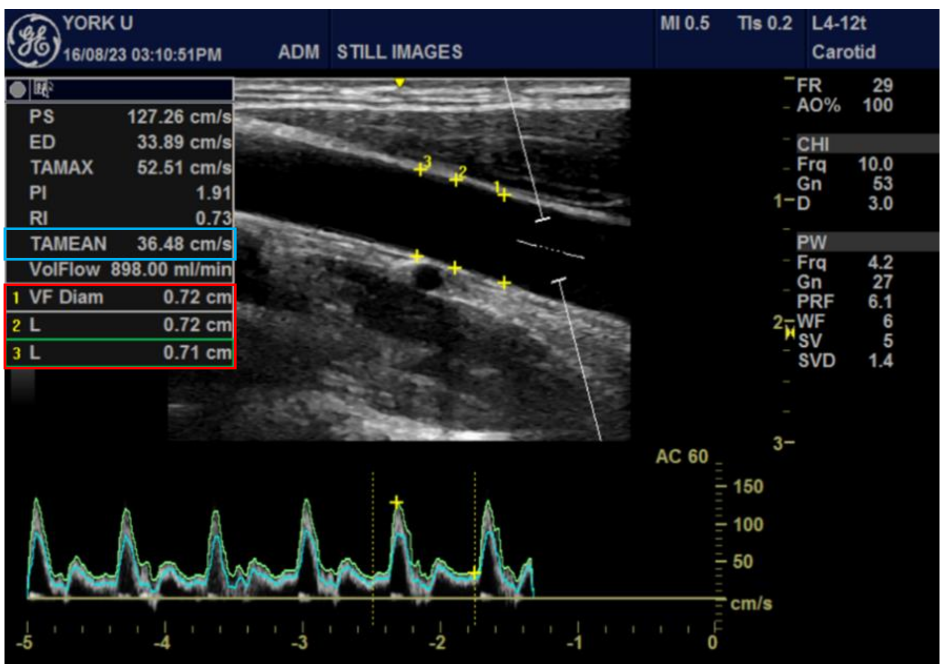

Figure 6. *Screen capture from a sample recording demonstrating the determination of velocity and vessel diameter during a single cardiac cycle. TAMEAN denotes the time averaged mean velocity and values 1, 2, and 3 (Respectively VF Diam, L, and L) denote vessel diameter measurements. TAMEAN is enclosed in blue and vessel diameters are enclosed in red.*

For each participant, blood flow volume (BFV) was then calculated in each vessel using the previously calculated mean velocities, as well as the mean vessel diameter values. The following formula was used to determine blood flow volume in millilitres per minute (ml/min):

$$\textit{Time-averaged velocity} \times \textit{cross-sectional area of the circular vessel} \text{ x 60 seconds}$$

$$= \textit{Time averaged velocity} \times [(\textit{vessel diameter}/2)^2 \times \pi] \text{ x 60 seconds.}$$ [55]

Statistical Analysis

Statistical analysis for this study was performed using the Statistical Package for the Social Sciences (SPSS) version 29. It is important to note that for the sake of this study, no blood flow volume measurements taken using the jig were analyzed. Any measurements made using the jig are to be analyzed in a future study conducted in the WHIPR lab. To determine intra-rater and inter-rater reliability of the blood flow measurements obtained in this study, Intraclass correlation coefficients (ICC) were calculated and reported alongside a 95% confidence interval (CI). These Intraclass correlation coefficients allowed for the assessment of absolute agreement between blood flow measurements. ICC values typically yield a value between 0 and 1, in which greater values indicate stronger levels of agreement.[41] The ICC model employed for this study was the two-way mixed effects, absolute agreement, multiple raters/measurements model (3, k). Furthermore, average measures ICCs were used in this study as the focus was to compare the reliability of mean blood flow volumes between two self-selected raters. This was determined using the guidelines defined by McGraw and Wong.[56] Each ICC value calculated in the study was categorized as defined in Table 1. Additionally, Bland-Altman analyses were used to evaluate agreement between the novice and experienced rater.[57]

Table 1. *Categorization of various Intraclass correlation coefficients (ICCs).*[43]

ICC Value	Reliability Categorization
<0.5	Poor
0.5 – 0.75	Moderate
0.75 – 0.9	Good
>0.9	Excellent

Using data from each eligible participant, four separate comparisons were made per blood vessel as described below. Comparisons 1 to 3 assessed inter-rater reliability between the novice and experienced sonographer's measurements with comparisons 4 and 5 respectively assessing the intra-rater reliability of the novice and experienced sonographer's measurements. Recall that in this thesis, the two series completed by the novice are denoted as series 1 and 2, and the singular series completed by the experienced sonographer is denoted as series 3.

Comparison 1: The first blood flow measurement taken by the novice in Series 1 compared to the first blood flow measurement taken by the experienced sonographer in series 3.

Comparison 2: The last blood flow measurement taken by the novice in Series 1 compared to the last blood flow measurement taken by the experienced sonographer in Series 3.

Comparison 3: The last blood flow measurement taken by the novice in Series 2 compared to the last blood flow measurement taken by the experienced sonographer in Series 3.

Comparison 4: The last blood flow measurement taken by the novice in Series 1 compared to the last blood flow measurement taken by the novice in Series 2.

Comparison 5: The first blood flow measurement taken by the experienced sonographer in Series 3 compared to the last blood flow measurement taken by the experienced sonographer in Series 3.

Chapter 3: Results

In total, 38 participants took part in the study, however 1 participant yielded invalid data and was therefore excluded entirely from statistical analysis. As a result, the data of 37 participants were accounted for when assessing reliability (mean age 19.92 years ±2.03). For each inter-rater reliability comparison, participants were only included if both sonographers were able to obtain a valid blood flow volume measurement. When calculating the intra-rater reliability of the novice sonographer's measurements, participants were included if the novice sonographer was able to obtain valid blood flow volume measurements during each of the two series they collected on. Each ICC value has been reported alongside their 95% confidence intervals, as can be seen in tables 2 to 5.

Inter-rater analysis of U/S measurements

When comparing the first BFV measurement taken by the novice in series 1 to the first measurement taken by the experienced sonographer in series 3 (Table 2), poor inter-rater reliability was found when assessing blood flow volume in the CCA (ICC = -.127) as well as the ICA (ICC = .066). Inter-rater reliability was found to be moderate with respect to the VA (ICC = .694). Regarding the negative ICC value obtained in the CCA, this suggests the ICC obtained by measuring blood flow volume in the CCA may be attributed to chance.[43]

Table 2. *ICC calculations assessing inter-rater reliability between the first BFV measurements taken by the novice in Series 1 and the first BFV measurements taken by the experienced sonographer in series 3.*

	CCA (n=34)	**ICA (n=30)**	**VA (n=31)**
ICC	-.127	.066	.694
95% CI	-.703 to .328	-.332 to .426	.172 to .871

Note; Poor = <0.5, Moderate = 0.5 to 0.75, Good = 0.75 to 0.9, Excellent = >0.9

Comparing the final measurements taken by the novice in series 1 with the final measurements taken by the experienced sonographer in series 3 (Table 3), poor inter-rater reliability was demonstrated when comparing BFV in the CCA (ICC = .203) and ICA (ICC = .192), with BFV in the VA yielding moderate reliability (ICC = .725)

Table 3. *ICC calculations assessing inter-rater reliability between the last BFV measurements taken by the novice in Series 1 and the last BFV measurements taken by the experienced sonographer in series 3.*

	CCA (n=34)	**ICA (n=29)**	**VA (n=31)**
ICC	.203	.192	.725
95% CI	-.364 to .565	-.248 to .539	.332 to .877

Note; Poor = <0.5, Moderate = 0.5 to 0.75, Good = 0.75 to 0.9, Excellent = >0.9

Comparing the final measurements taken by the novice in series 2 with the final measurements taken by the experienced sonographer in series 3 (Table 4), poor inter-rater reliability was demonstrated when comparing BFV in the CCA (ICC = .445) and ICA (ICC = .321), with BFV in the VA yielding moderate reliability (ICC = .696).

Table 4. *ICC calculations assessing inter-rater reliability between the last BFV measurements taken by the novice in Series 2 and the last BFV measurements taken by the experienced sonographer in series 3.*

	CCA (n=35)	**ICA (n=32)**	**VA (n=31)**
ICC	.445	.321	.696
95% CI	-.181 to .741	-.190 to .640	.016 to .884

Note; Poor = <0.5, Moderate = 0.5 to 0.75, Good = 0.75 to 0.9, Excellent = >0.9

Within each participant, blood flow measures used in the ICC calculations of table 2 were taken first, followed by the blood flow measures used in the ICC calculations of table 3, and lastly blood flow measures used in the ICC calculations of table 4 (same measure was used for experienced sonographer in tables 3 and 4 but different measure was used for novice in tables 3 and 4 since the novice collected an additional series of measurements).

Across all inter-rater comparisons, Bland-Altman analysis indicated the underestimation of blood flow volume by the novice relative to the experienced sonographer (Figures 7-9).

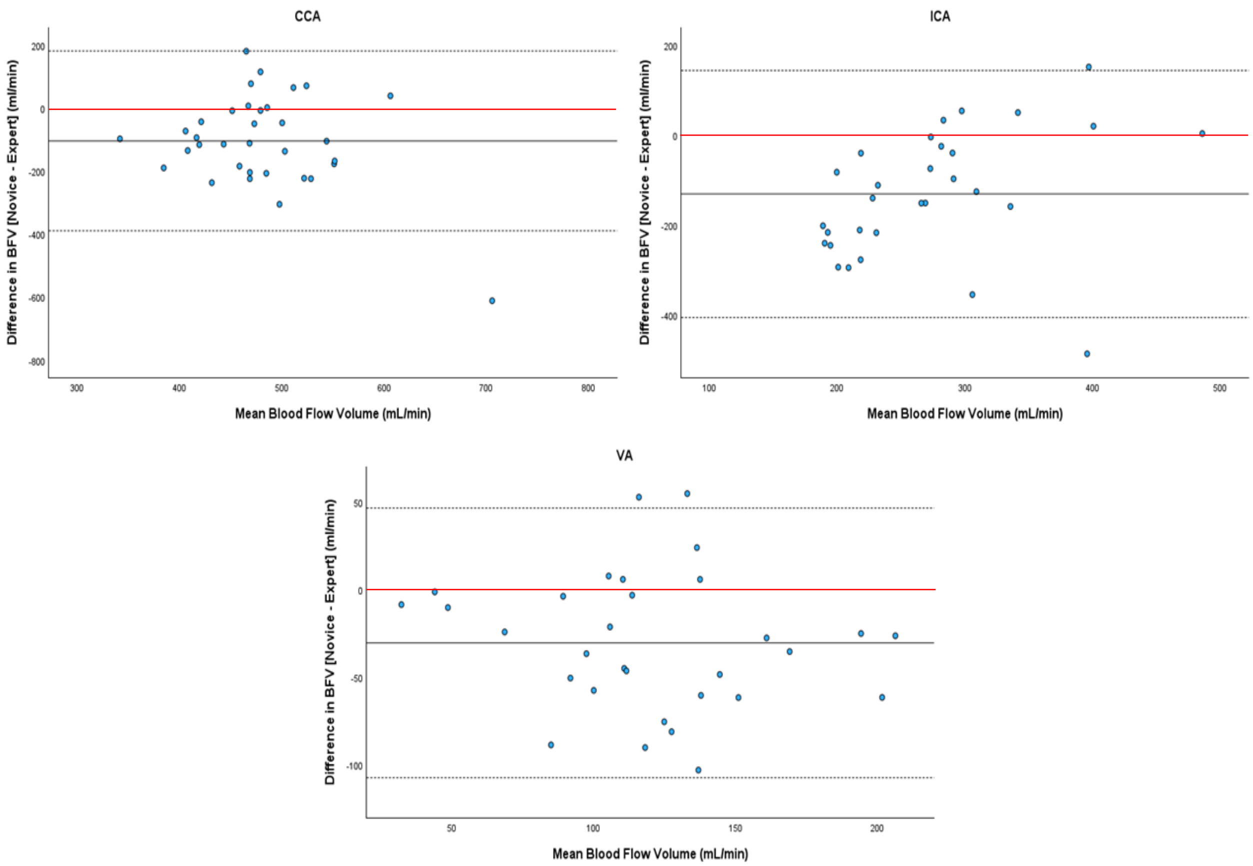

Figure 7. *Bland-Altman plots indicating agreement of the first BFV measurements taken by the novice in Series 1 compared to the first BFV measurements taken by the experienced sonographer in Series 3 in the CCA (top left), ICA (top right), and VA (bottom). The red line represents total agreement between sonographers; the novice sonographer underestimated blood flow volume relative to the experienced sonographer.*

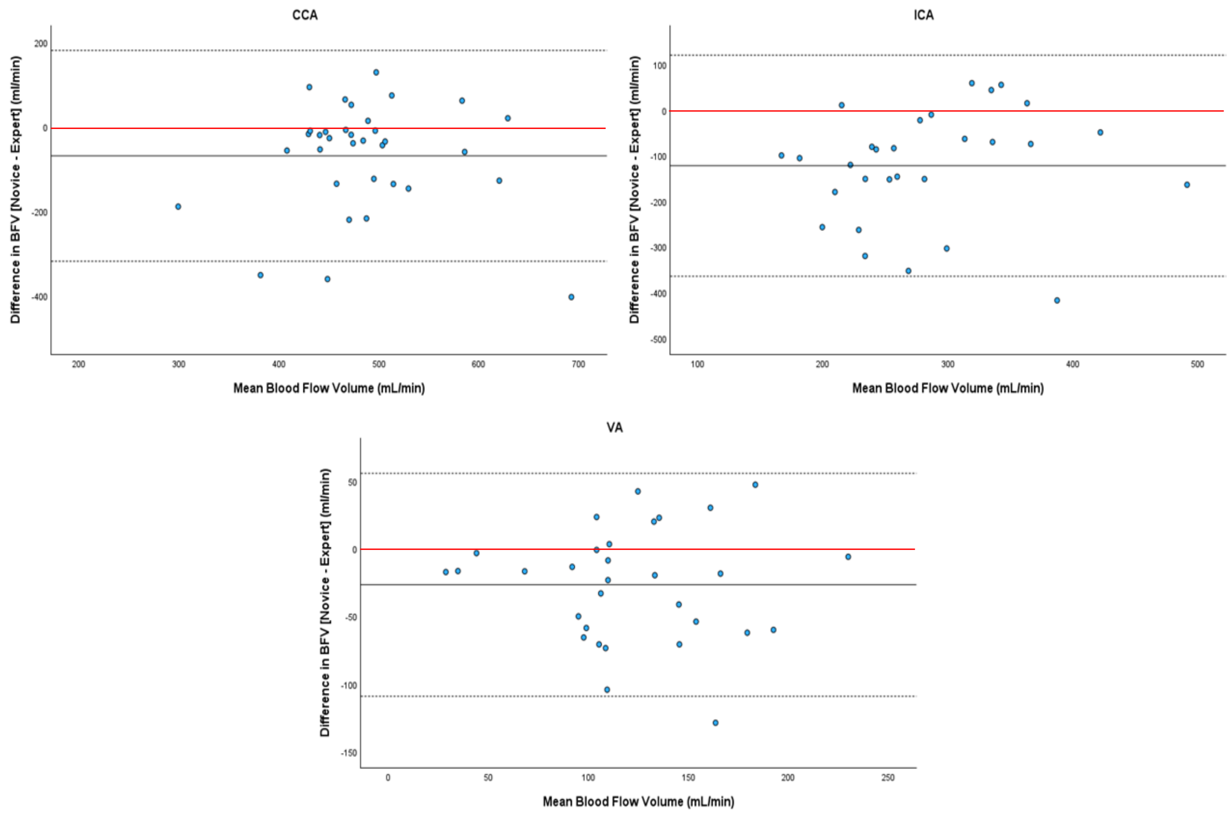

Figure 8. *Bland-Altman plots indicating agreement of the last BFV measurements taken by the novice in Series 1 compared to the last BFV measurements taken by the experienced sonographer in Series 3 in the CCA (top left), ICA (top right), and VA (bottom). The red line represents total agreement between sonographers; the novice sonographer underestimated blood flow volume relative to the experienced sonographer.*

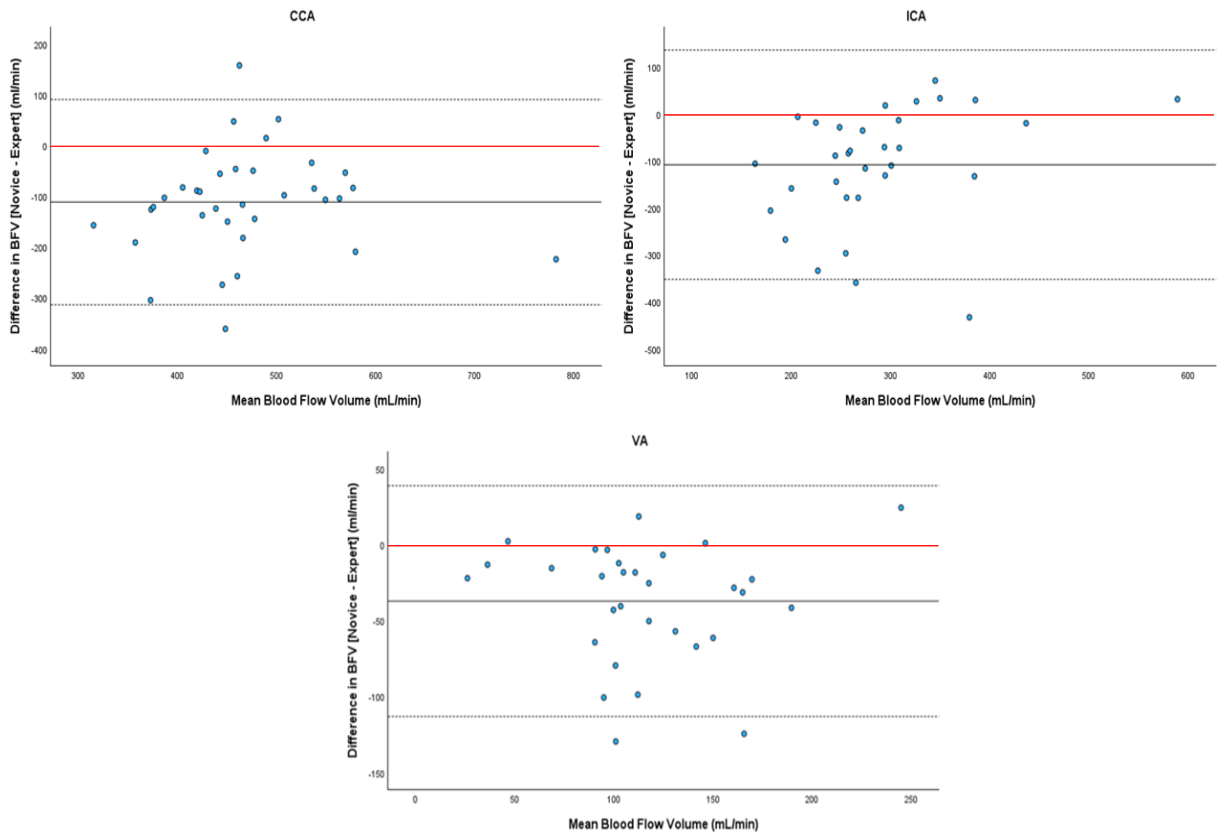

Figure 9. *Bland-Altman plots indicating agreement of the last BFV measurements taken by the novice in Series 2 compared to the last BFV measurements taken by the experienced sonographer in Series 3 in the CCA (top left), ICA (top right), and VA (bottom). The red line represents total agreement between sonographers; the novice sonographer underestimated blood flow volume relative to the experienced sonographer.*

Intra-rater analysis of U/S measurements

Upon analyzing the last blood flow measurements taken by the novice in Series 1 compared to Series 2 (Table 5), moderate intra-rater reliability was found in the CCA (ICC = .701) and ICA (ICC = .729), whereas good intra-rater reliability was demonstrated in the VA (ICC = .818).

Table 5. *ICC calculations assessing intra-rater reliability between the last BFV measurements taken by the novice in Series 1 and the last BFV measurements taken by the novice in Series 2.*

	CCA (n=34)	**ICA (n=31)**	**VA (n=31)**
ICC	.701	.729	.818
95% CI	.400 to .851	.442 to .869	.621 to .912

Note; Poor = <0.5, Moderate = 0.5 to 0.75, Good = 0.75 to 0.9, Excellent = >0.9

To compare the novice sonographer's intra-rater reliability, the experienced sonographer's intra-rater reliability was also calculated and included in Table 6. When comparing the first measurement taken by the experienced sonographer to the last measurement taken by the experienced sonographer in series 3, excellent intra-rater reliability was found across all vessels.

Table 6. *ICC calculations assessing intra-rater reliability between the first BFV measurements taken by the experienced sonographer in Series 3 and the last BFV measurements taken by the experienced sonographer in Series 3*

	CCA (n=34)	**ICA (n=31)**	**VA (n=31)**
ICC	.957	.977	.980
95% CI	.917 to .978	.954 to .988	.959 to .990

Note; Poor = <0.5, Moderate = 0.5 to 0.75, Good = 0.75 to 0.9, Excellent = >0.9

Chapter 4: Discussion

The objective of this study was to assess the intra-rater and inter-rater reliability of blood flow measurements of the left common carotid, internal carotid, and vertebral artery, using duplex Doppler ultrasound on a presumably healthy university aged population. This study specifically sought to examine the differences in the reliability of these measures when taken by a novice compared to an experienced sonographer. Two separate hypotheses were made, the first being that across all vessels, U/S BFV measurements would demonstrate at least moderate inter-rater reliability between the novice and experienced sonographers (ICC 0.5-0.75). The second hypothesis predicted that across all vessels, U/S BFV measurements would demonstrate at least moderate intra-rater reliability within the novice.

When assessing inter-rater reliability, the calculated ICC values demonstrated poor reliability in the ICA and CCA, and moderate reliability in the VA, therefore rejecting the first hypothesis. In the assessment of intra-rater reliability, ICC values demonstrated moderate reliability in the CCA and ICA, and good reliability in the VA when taken by the novice, and excellent reliability in all vessels when taken by the experienced sonographer. This confirms the second hypothesis. Based on these findings, it may not be suitable for both a novice and experienced sonographer to assess blood flow volume of the neck in the same subject during longitudinal studies (e.g., assessing blood flow in varsity athletes pre- and post-concussion), however intra-rater findings demonstrated that DDU is a reliable method of assessing BFV when used by the same sonographer.

Regarding inter-rater analysis, despite ICC values demonstrating poor reliability in the CCA and ICA, it should be noted that the ICC values increased when comparing the ICCs of the first measurements to the ICCs of later measurements (Tables 2-4). Recall that within each participant, the data collected to form each table was collected chronologically (Data from table 2 was collected the first, then table 3, then data from table 4 was collected last). In other words, these findings demonstrate that the novice's BFV measurements were closer in agreement with the experienced sonographer's measurements as more measurements were taken. This suggests that increased practice may have influenced the novice sonographer's ability to obtain increasingly similar measurements to the experienced sonographer.

The generally low reliability of these measures led to further analysis involving the reliability of TAMEAN and vessel diameter measurements. Recall that TAMEAN and vessel diameter values were obtained for each participant using the ultrasound, which allowed for the calculation of blood flow volume. When comparing the ICCs of BFV, TAMEAN, and vessel diameter, inter-rater analysis indicated greater absolute agreement between the novice and experienced sonographer in TAMEAN and vessel diameter in comparison to BFV (Table 7). As a result, TAMEAN and vessel diameter generally yielded greater inter-rater reliability than BFV. Inter-rater analysis demonstrated similar findings as there was greater absolute agreement between the novice in series 1 and 2 for TAMEAN and vessel diameter in comparison to BFV (Table 8).

Table 7. *ICC values for inter-rater reliability comparisons of Blood Flow Volume (BFV), Mean Time-Averaged Velocity (TAMEAN), and Mean Vessel Diameter between novice and experienced sonographer.*

		BFV		TAMEAN		Diameter	
Comparison	**Vessel**	**ICC**	**95%CI**	**ICC**	**95%CI**	**ICC**	**95%CI**
Novice 1st measurement in series 1 & experienced 1st measurement in series 3	**CCA**	-.127	-.703 to .328	.421	-.167 to .712	.616	-.082 to .844
	ICA	.066	-.332 to .426	-.220	-1.361 to .391	.496	-.191 to .784
	VA	.694	.172 to .871	.465	-.027 to .730	.925	.476 to .977
Novice last measurement in series 1 & experienced last measurement in series 3	**CCA**	.203	-.364 to .565	.564	.120 to .783	.605	-.089 to .838
	ICA	.192	-.248 to .539	.276	-.448 to .652	.450	-.210 to .759
	VA	.725	.332 to .877	.632	.235 to .825	.935	.112 to .984
Novice last measurement in series 2 & experienced last measurement in series 3	**CCA**	.445	-.181 to .741	.625	.242 to .814	.696	-.116 to .892
	ICA	.321	-.190 to .640	.556	.101 to .782	.507	-.224 to .801
	VA	.696	.016 to .884	.527	-.017 to .778	.932	.648 to .977

Table 8. *ICC values for intra-rater reliability comparisons of Blood Flow Volume (BFV), Mean Time-Averaged Velocity (TAMEAN), and Mean Vessel Diameter in novice sonographer.*

		BFV		**TAMEAN**		**Diameter**	
	Vessel	**ICC**	**95%CI**	**ICC**	**95%CI**	**ICC**	**95%CI**
Novice last measurement in series 1 & novice last measurement in series 2	**CCA**	.701	.400 to .851	.709	.367 to .860	.883	.767 to .941
	ICA	.729	.442 to .869	.745	.475 to .876	.861	.716 to .932
	VA	.818	.621 to .912	.776	.475 to .898	.967	.931 to .984

Recall that to calculate BFV, TAMEAN and vessel diameter were obtained and then substituted into the following formula:

Time-averaged velocity × *cross-sectional area of the circular vessel* x 60 seconds

$= \textit{Time averaged velocity} \times [(\textit{vessel diameter}/2)^2 \times \pi]$ x 60 seconds.[55]

It is important to note that TAMEAN and vessel diameter are both metrics that are heavily influenced by the sonographer. This means the calculation of blood flow volume involves two sources of variability caused by the sonographer, implying any variability impacting the measurements of TAMEAN or vessel diameter are also included in the final calculation of BFV. Consequently, there are more sources of variability involved in the calculation of BFV when compared to TAMEAN and vessel diameter individually. This may explain why the ICCs for BFV were generally lower than that of TAMEAN and vessel diameter (Tables 7, 8). Furthermore, the breadth in the sources of variability when measuring BFV may explain why within the review of the literature, there is a lack of studies assessing the reliability of BFV in these vessels compared to other blood flow metrics such as peak systolic velocity.[45]

The calculation of TAMEAN introduces variability to the overall calculation of BFV due to potential disparities in measurements between the novice and experienced sonographer. It is cited within the literature that there are numerous human factors which introduce error to Doppler blood velocity measurements including lack of experience, system noise, incorrect adjustment of the probe to vessel angle, and inappropriate selection of sample volume box size.[58, 59] Because of this, there are a multitude of factors that may have impacted the overall reliability of TAMEAN measurements, therefore impacting the reliability of the calculated BFV values.

As mentioned previously, vessel diameter measurements are also heavily influenced by the sonographers as these measures, when taken manually, rely on individual judgement to determine the size of each vessel lumen. As a result, this presents a potential source of variability for BFV in this study. Variability of manual vessel diameter measurements has been explored in the literature by comparing manual diameter measurements to those taken using edge detection software, which is an automated method allowing for the determination of metrics including vessel diameter.[60] Previous study results have shown that edge detection greatly reduces the subjectivity associated with manual measurements.[61] The literature has also demonstrated edge detection yielding different vessel diameters from manual measurements in other vessels such as the brachial artery.[62] This suggests that calculating CCA, ICA, and VA vessel diameters in this study may yield different results when done manually compared to when using edge detection. In turn, the potential differences in diameters obtained with and without edge detection could result in differences in the ICCs of BFV. As a result, it could be useful to compare BFV with and without edge detection software to determine which modality yields higher inter-rater and intra-rater reliability among a novice and experienced sonographer.

Limitations

It is important to note that there are limitations to this study. Firstly, U/S is an operator dependent mode of imaging, meaning results are highly dependent on the skill and/or judgement of the sonographers.

As previously noted, various human factors can introduce errors in the assessment of blood flow velocity. This serves as a limitation in this study as these factors may have impacted the quality of the obtained TAMEAN measurements, introducing variability in the collection of TAMEAN. Consequently, the collected TAMEAN values may not have been representative of participants' true TAMEAN values at the time of the study. Furthermore, blood vessel diameters were manually measured by both the novice and experienced sonographer, meaning individual judgement from the sonographers in their respective vessel diameter measurements may have also introduced variability in the study. An alternative method of assessing blood vessel diameter is by using edge detection software. With respect to diameter measurements, this would remove any potential bias from the novice or experienced sonographer as it would remove their involvement in measuring. Resultantly, future studies should consider the use of edge detection software when measuring vessel diameters. If not, the reliability of diameter measures should be assessed in addition to the reliability of blood flow.

Additionally, though it was expected for the experienced sonographer's measurements to be valid when collected using DDU, this study did not investigate these measurements against a benchmark comparator such as MRI. As a result, the validity of these measurements cannot be confirmed. Consequently, despite being more reliable, it cannot be confirmed that the experienced sonographer's measurements were any more or less valid than those collected by the novice sonographer.

Lastly, although 37 participants were included in statistical analysis, not all 37 participants were included in each comparison. Recall that for each inter-rater reliability comparison, participants were included if both sonographers were able collect a valid blood flow volume measurement. Furthermore, for each intra-rater reliability comparison, participants were included if the novice sonographer was able to obtain a valid blood flow volume measurement during each of the two series they collected on. As a result, if one sonographer was able to obtain valid data but the other was not, or if the novice sonographer was only able to obtain valid data in one of the two series, then this data was omitted from the reliability comparisons, potentially acting as a source of bias when assessing reliability.

Chapter 5: Future Directions and Conclusions

Future Directions

Future reliability studies should consider involving more sonographers with similar levels of experience to gain a better understanding of the overall intra-rater and inter-rater reliability of DDU in assessing neck vasculature BFV. For instance, comparing the inter-rater reliability of blood flow measures between multiple experienced sonographers may help understand whether the lack of inter-rater reliability between novice and experienced sonographers can be attributed to a skill disparity, or if it is simply due to the overall lack of reliability of DDU measurements in the neck vasculature. Furthermore, future studies should also consider including sonographers with various levels of experience (e.g., novice, intermediate, experienced). In doing so, suggestions could be provided on what kind of experience a sonographer should amass to reliably assess blood flow in the neck vasculature. As recommended previously, future studies should also consider implementing the use of edge-detection software when assessing vessel diameter to reduce potential bias due to the subjectivity of sonographers. In the context of this study, edge detection software may reduce bias as all vessel diameter measurements would be completed by the same rater (i.e., the software), therefore eliminating potential individual biases in diameter measurements by the novice and experienced sonographers.

Within the WHIPR lab, future research will aim to analyze the blood flow data that was collected using the jig, as the use of a jig may help improve the reliability of collected blood flow measurements. The results from this current study will allow for comparisons to be made between measurements obtained with and without the use of the jig, across both the novice and experienced sonographers. This will allow for the determination of whether using a jig can increase the intra-rater and inter-rater reliability of blood flow measurements collected in the left

CCA, ICA, and VA. These findings will inform future research methodologies with respect to whether a jig should or should not be employed when assessing blood flow in the neck.

Conclusions

By comparing the inter and intra-rater reliability measures of blood flow between a novice and experienced sonographer, this study provides insight regarding the ability of a novice sonographer to reliably assess blood flow in the neck compared to an experienced sonographer. Poor inter-rater reliability in the CCA and ICA and moderate inter-rater reliability in the VA was found between the novice and experienced sonographer, suggesting an overall lack of reliability when obtaining blood flow measurements in the neck vasculature. Despite the novice demonstrating moderate to good intra-rater reliability, further training should be required for a novice to more reliably measure BFV. This highlights the importance of having a consistent sonographer during longitudinal studies to reduce variability of results. Future studies looking to assess BFV in the neck vasculature should attempt to mitigate bias in the collection of TAMEAN and diameter measures as a means of increasing reliability of BFV measurements.

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