

Relationship between Handedness and the Geometry of the Branches of the Aortic Arch

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Abstract

Handedness is the most obvious behavioural asymmetry in humans. Asymmetrical regional cerebral blood volume changes, particularly in the left premotor and parietal regions, occur contralateral to hand dominance during mental and motor activity. While a potential link between hemispheric and anatomical lateralisation has been investigated, research into the influence of asymmetrical vascular geometry is severely lacking. This study explores the relationship between handedness and the geometry of the arterial branches of the aortic arch, analysing potential asymmetries between the left common carotid (LC) and the combined right common carotid and brachiocephalic trunk (RC-BT complex) of left-handed and right-handed individuals. Selected geometric parameters of the vessels were measured, including minimum, mean, and maximum diameters, length, angle deviation, mean artery angle, and calculated resistance to blood flow. A revised version of the Edinburgh Handedness Inventory classified a sample of 71 participants, aged 21 to 96, into relevant handedness categories (left-handed = 8; right-handed = 62). An in-depth analysis of computed tomography angiography scans with RadiAnt DICOM Viewer (64-bit) imaging software was conducted. The findings confirm that right-handed individuals had dominant LC arteries (21.57% increased flow) that are presumably responsible for the higher metabolic demand of the left hemisphere of the brain (5.7%) in such individuals. Conversely, left-handed individuals had dominant RC-BT complex arteries (61.57% increased flow) that are responsible for a higher metabolic demand of the right hemisphere (16.21%). This difference was particularly evident in the geometric parameters of minimum and maximum arterial diameters, and calculated resistance to blood flow. Measurements of right-handers' alternate arterial branching patterns showed a significant increase in overall blood flow resistance in both vessels, with a particular increase in RC-BT complex resistance. Therefore, despite the branching abnormality, a handedness-related bias was still evident. The findings concur with existing hemodynamic studies of the carotid arteries.

Keywords: handedness, cerebral lateralisation, language, aortic arch, common carotid artery, arterial geometry.

Introduction

Handedness is the most obvious behavioural asymmetry in humans (Cagnie, Petrovic, Voet, Barbaix, & Cambie, 2006). Given its relation to hemispheric asymmetry of cognitive functions, principally language, the phenomenon of lateral manual preference has been of interest to neuropsychologists for years (Reiss & Reiss, 1999). However, the neurobiological basis for hand preference, and therefore for neurocognitive asymmetry, is still not understood (Amunts, Jancke, Mohlberg, Steinmetz, & Zilles, 2000). Nevertheless, it has become clear that handedness interacts with a number of variables, including aspects of hemispheric lateralization, sex, age, family history, writing posture, and the type of lateralized task (Hannay, 1988).

Various studies have investigated genetic, neurobiological, and socio-cultural aspects of handedness. This study investigates the hypothesis that handedness is strongly associated with asymmetrical cerebral blood flow caused by the asymmetrical vascular anatomy of the human body, particularly asymmetries in the arterial geometry of branches of the aortic arch.

Background

Handedness is not a straightforward a topic. A distinction needs to be made between hand preference and hand proficiency, while the evaluation of hand preference is also contentious. Some researchers focus solely on hand preference during writing tasks, while others evaluate it over a number of activities, placing handedness on a continuum ranging from extreme right-handed (RH) at one end of the scale, extreme left-handed (LH) at the other, and ambidextrousness in between (Zillmer, Spiers & Culbertson, 2008).

Researchers who define handedness through the assessment of efficient task completion emphasise proficiency as the determining factor of hand dominance (Zillmer et al., 2008). Although a positive correlation has been demonstrated repeatedly between these two perspectives, some studies reveal dissociation, suggesting that asymmetrical preference and proficiency are distinct entities (see Triggs, Calvanio, Levine, Heaton, & Heilman, 2000 for review).

Between 6 and 16% of the world's population is LH, and 2 to 3% are ambidextrous, showing no clear hand preference or proficiency. However, studies frequently group ambidextrous participants with LH ones, causing the two-way comparison between RH and non-RH to be more common in research than between RH and LH (Thillers, MacDonald, & Herlitz, 2007).

Left-handedness is more common in males (13%) than in females (11%) (Thillers et al., 2007; Vuoksima, Koskenvuo, Rose, & Kaprio, 2009). A meta-analysis of 43 studies suggests that LH males are up to 25% more common than LH females (Sommer, Aleman, Somers, Boks, & Kahn, 2008). These sex differences are greater in non-Western samples than in Western ones, suggesting that cultural (or possibly racial) factors are moderators of handedness (Sommer et al., 2008).

Failure to understand the biological origins of handedness has resulted in the historical stigmatisation of LH individuals. This norm deviation has been perceived historically as an indication of mental deficiency, sickliness, undesirability, incompetence, and clumsiness (Porac & Martin, 2007). As a result, the tradition of “converting” left-dominant individuals is a social practice common in many cultures (Provins, 1997). Forced conversion from a young age is associated with memory disorders, concentration deficits, dyslexia problems, spatial disorientation, and disorders of fine motor skills (Sattler, 2004). Investigating the biological substrates of handedness is imperative in moving towards alleviating social stigmatisation and subsequent problematic “conversion” practices (Siebner et al., 2002).

Mechanisms of Handedness

Decussation of the sensory and motor tracts from the brain to the spinal cord results in the right cerebral hemisphere showing greater involvement in the sensory motor control and representation of the left side of the body, whereas the left hemisphere is more associated with the right side (Zillmer et al., 2008). Although the relationships between different aspects of hemispheric lateralisation are still speculative, the strong association between handedness, language, and motor

functioning has led researchers to use handedness as an indirect indicator of hemispheric specialization (Dadda, Cantalupo, & Hopkins, 2006).

Despite uncertainty surrounding the origins of handedness, neuropsychological studies of asymmetric clinical phenomena such as aphasia have shown that in addition to their contralateral control of sensory motor functioning, the two cerebral hemispheres of the brain mediate different cognition functions (Herve, Crivello, Perchey, Mazoyer, & Tzourio-Mazoyer, 2006). In RH individuals, the left hemisphere mediates language and praxic functions, whereas the right hemisphere is more involved in visuospatial and attentional functions (Josse & Tzourio-Mazoyer, 2004). Left-handers are less laterally differentiated than RH individuals, as evidenced by their relative bilaterality of language functioning, and by the presentation of transient aphasia following left hemisphere lesions (Knecht et al., 2000). The LH population is heterogeneous with respect to the direction of lateralization, with approximately 60% reflecting RH lateralisation, whereas roughly 40% have a reverse pattern (Roberts, 1969).

Most handedness studies correlate anatomical asymmetries of the brain with handedness, such as the size of the frontal and occipital lobes, and the upper lift of the right sylvian fissure (Josse, Segheir, Kherif, & Price, 2008). However, none of these studies successfully identified a biological substrate of these anatomical asymmetries (Herve et al., 2006). Importantly, however, direction of causality cannot be inferred from these correlation studies (Beaton, 1997).

Few studies have focused on other (non-cerebral) anatomical asymmetries directly related to handedness. Older suppositions dating from the 19th and the beginning of the 20th century proposed that a number of possible variables played a role in determining handedness, including arm length, asymmetries in the blood supply to the extremities, and bone-weight (Amunts et al., 2000).

Handedness and Asymmetrical Blood Flow

The hypothesis that hemispheric lateralisation is related to asymmetrical cerebral blood flow and therefore to asymmetries in the vascular system, is not new (Cagnie et al., 2006). Blood flow to the brain is closely associated with metabolic requirements of the tissue for glucose and oxygen (Siesjo, 1978). However, large increases in flow are necessary to produce small increases in oxygen metabolic rates. Buxton and Frank (1997) approximate this required flow increase to be 19% for a 5% enhancement in localised cerebral oxygen metabolism. Identifying these regional variations in blood flow forms the basis for mapping localised brain activation patterns, such as positron emission tomography and functional magnetic resonance imaging (Buxton, Wong, & Frank, 1998).

Regional cerebral blood volume changes during mental and motor activity (Rijsberg & Ingvar, 1968). Studies have shown that activation of the contralateral primary motor cortex and dorsal premotor cortex is 20 times stronger than the activation of the ipsilateral cortex during complex distal hand movements (Haaland, Elsinger, Mayer, Durgerian, & Rao, 2004; Kim et al., 1993; Vivani, Perani, Grassi, Bettinardi, & Fazio, 1998). Right-handers with brain damage show greater ipsilateral motor impairment following left hemisphere damage versus right hemisphere damage (Haaland & Harrington, 1996). Handedness therefore reflects functional hemispheric asymmetry during motor control. The nature and extent of this asymmetry and its relation to hemispheric dominance have long been debated (Kim et al., 1993; Vivani et al., 1998). An extreme hypothesis argues that movement is initially generated in the dominant hemisphere and is subsequently replicated in the non-dominant one (Geschwind, 1975). This hypothesis is supported by studies of identical rhythmic movements, which illustrate that during the performance of motor tasks, the dominant hand leads the non-dominant one by approximately 25 ms, irrespective of movement speed (Stucchi & Vivani, 1993).

Arteriographic studies conclude that the mechanical properties of large arteries play an important role in regulation of cerebral blood flow (Magun, 1973; Nichols & O'Rourke, 1998).

Each artery resists blood flow based on its geometric features, forming an important pressure gradient across the arteries between the aorta and the large arteries of the brain (Kanzow & Dieckhoff, 1969). Luminal diameter serves as the most influential geometric property related to blood flow resistance (Ku, 1997; Lusic, 2000; Mitchell, 2003; 2004). However, side branches and mild curvatures as low as 15° are sufficient to impede blood flow (Banerjee, Cho & Back, 1992; Manbachi, Hoi, Wasserman, Lakatta, & Steiman, 2011; Staalsen et al., 1995). This alteration in flow is a result of swirling, flow separation, and secondary flow (Doorly & Sherwin, 2009; Ku, 1997). Investigating the geometry of the larger arteries that feed the brain is important for the identification of asymmetrical cerebral blood flow and blood flow resistance.

Recent studies investigating this relationship are based on the assumption that RH individuals have dominant left vertebral arteries, and vice-versa for LH individuals (Zaina et al., 2003). The vertebral arteries were focused upon because they lead directly to the brain, and because variations in the normal anatomy of the extracranial vertebral arteries are relatively common (Cagnie et al., 2006). Significant variations in diameter, flow velocities, and flow volume have been recorded between the two vertebral arteries, as the left vertebral artery typically has more dominant blood flow than the right (Jeng & Yip, 2004). However, a correlation analysis between the diameter of the vessels and hand dominance failed to produce significant results (Cagnie et al., 2006). This could be due to the small sample size — only 50 participants were included (29 RH, 21 LH).

Vertebral arteries are not the most appropriate place to look for the sources of asymmetrical cerebral blood flow. These two arteries, which stem from the left and right subclavian arteries, feed the basilar artery, which in turn splits into the right and left posterior cerebral arteries (Figure 1). Therefore, geometric asymmetries in the vertebral arteries are irrelevant for investigating asymmetrical cerebral blood delivery because they merge into a single source of posterior cerebral blood flow. Contrastingly, the right and left internal carotid arteries feed the most asymmetrical region of the brain directly and independently (Figure 1). Therefore, branching and geometrical

asymmetries in these arteries should be key to exploring asymmetrical cerebral blood flow (Mitchell, 2004).

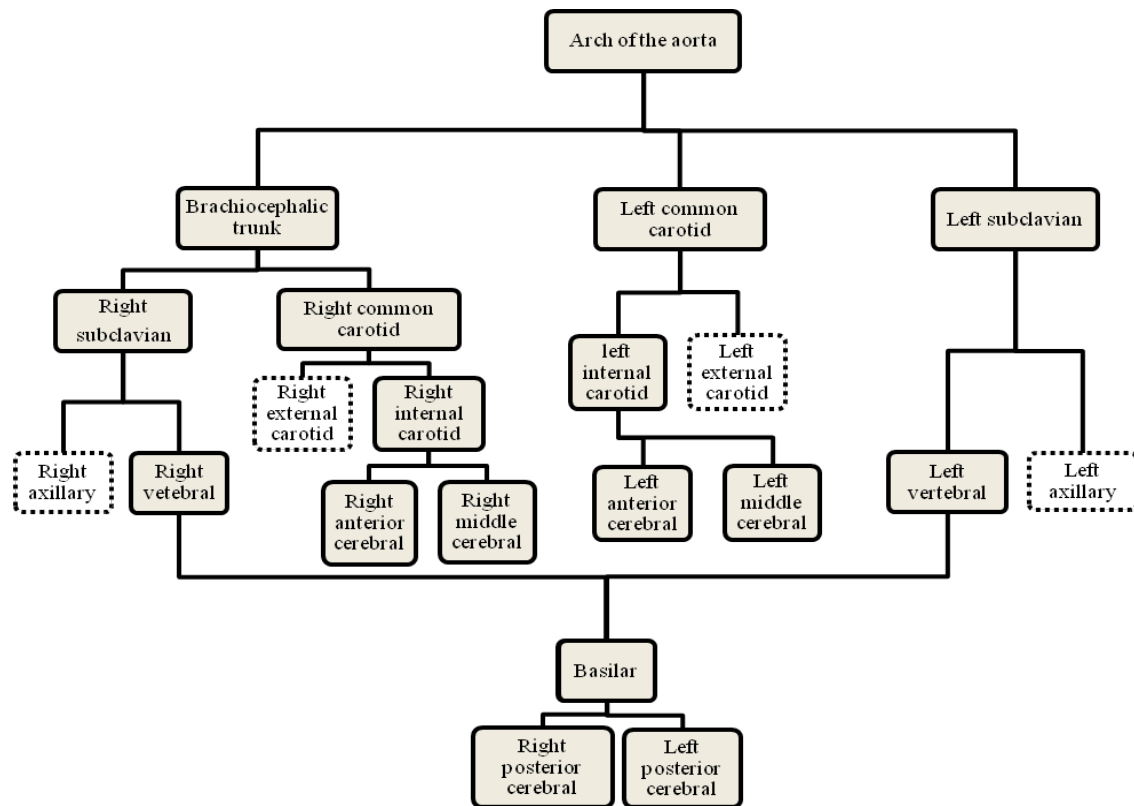


Figure 1. Scheme of distribution of the conventional arterial branching pattern

Disparities in flow rates between the right and left internal carotid arteries have been reported in relation to handedness. Bogren, Buonocore and Gu (1994) established normal carotid artery flow rates in five LH and five RH individuals, with the RH having higher flow rates in the left internal carotid artery than in the right, and the LH having higher flow rates in the right internal carotid artery ($p = .007$). However, the internal carotid arteries branch from larger vessels that originate at, or are close to, the aortic arch. Therefore, cerebral blood flow should also be directly influenced by the geometry of these core vessels. However, no significant differences in left and right common carotid artery flow rates were found by Bogren et al. (1994), possibly due to their small sample size.

Aging results in significant changes in the structure and function of the cardiovascular system, including increased arterial wall thickening, which has been shown to occur asymmetrically

(Oxenham & Sharpe, 2003). Onbas et al. (2007) confirm that handedness is a significant factor influencing intima-media thickness of the common carotid arteries, as hemodynamic stress and intimal damage is larger in the LC in RH compared to LH individuals. This provides indirect evidence of physiological asymmetry of functions, as intima-media wall thickening is highly associated with shear stress (Shaaban & Duerinckx, 2000).

Further vascular asymmetries are found in the conventional aortic arch branching pattern. Even though in most mammals the two common carotid arteries branch symmetrically from the brachiocephalic trunk (BT), a human branching asymmetry is evident. The RC shares a common trunk with the right subclavian artery (RS), stemming from the BT, whereas the LC and left subclavian artery (LS) stem directly from the aortic arch (Alsaif & Ramadan, 2010) (Figure 1 and 2). Arteries feeding the right hemisphere branch four times before reaching the hemisphere, whereas arteries feeding the left hemisphere branch three times. This asymmetry predicts decreased blood flow efficiency in the arterial path feeding the right hemisphere, as additional branching results in blood flow disturbance, decreased vessel diameter, and increased vessel angle deviation (Tortora & Derrickson, 2006). Furthermore, handedness is symmetrical in most mammals with symmetric aortic branching, whereas humans display a large RH bias (Carmon, Harishanu, Lowinger, & Lavy, 1972).

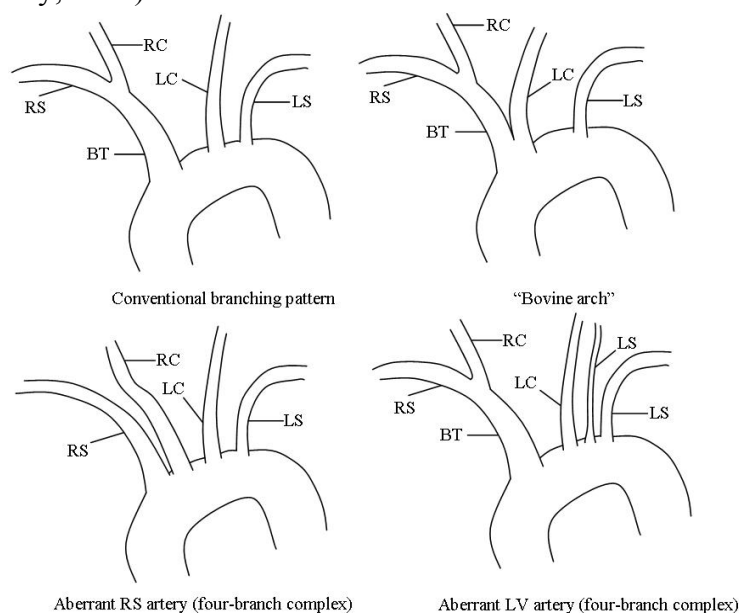


Figure 2. Common variations of aortic arch branching patterns.

Variation in the anatomy of the arch and its branches in humans is mostly asymptomatic. The most common branch variant, the “bovine arch”, occurring in approximately 20% of the population, results in symmetrical arterial branching of the LC and RC (Figure 2) (Alsaif & Ramadan, 2010; Gupta & Sodhi, 2005). Other less common variations, where an aberrant RS arises directly out of the aortic arch, also occur (Figure 2) (Jakanani & Adair, 2010; Kanne & Godwin, 2010). Abnormal branching patterns at the level of the aortic arch may cause all the above-mentioned vessels to independently contribute to cerebral blood flow in varying ways, making it imperative to investigate branching patterns and their unique geometrical characteristics when assessing asymmetrical blood flow (Tortora & Derrickson, 2006).

These findings raise questions regarding the relationship between the geometric and branching asymmetry of the primary aortic branches and hand dominance (as a measure of cerebral asymmetry). Despite this clear theoretical difference, the relationship between hand dominance and asymmetries of the common carotid arteries remains uninvestigated. A dearth of knowledge exists regarding the role that variation in the geometry and branching of these vessels may play on cerebral blood flow and consequently on handedness.

Aims and Hypothesis

Evidence linking handedness to blood flow in the LC and the RC-BT complex is lacking. Through an analysis of computed tomography angiography (CTA) scans, this study sought to measure vessel diameter, area, length, angle deviation from 90°, artery angle, and resistance to blood flow of the LC and the RC-BT complex in order to explore the relationship between the geometry of two branches of the aortic arch and handedness and thereby lateralisation of cognitive functioning. The following hypothesis was examined:

H₁: In individuals with conventional aortic branching patterning, the geometric characteristics of the LC and the RC-BT complex are indicative of an increased blood supply in the artery that lies contralateral to the hand dominance.

The following questions were addressed:

1. Are there significant geometric differences between the LC and the RC-BT complex in LH versus RH individuals?
2. Is there a relationship between the geometric characteristics of the LC and the RC-BT complex and handedness?
3. What combination of these variables, if any, predicts handedness?
4. How do unconventional branching patterns influence these characteristics and this potential relationship?
5. How does the socialised alteration of handedness influence these characteristics and this potential relationship?

Design and Methods

Design and Setting

This study nested within a larger research project, and aimed to investigate cerebral asymmetrical blood flow and its relation to handedness. A non-experimental quantitative design was utilised, allowing for analysis of numerical data. This study was relational, involving the measurement of potential relationships between handedness and multiple geometric asymmetries of the LC and the RC-BT complex. These variables were selected because of the strong theoretical basis for their direct influence on arterial blood flow. Analysis of the appropriate arteries took place at a Gatesville Medical Centre in Cape Town, where CTA scans are stored in digital format.

Participants

The CTA scans of 122 radiology patients (73 males and 49 females ranging between the ages of 16 and 96 years, mean 57 years) were collected from nine branches of a radiology practice. All patients who had CTA scans between 2009 and 2012 were included — this ensured the use of recent data, collected with the same modern technologies and procedures, and made it likely that participants were available for questioning concerning their handedness. A non-randomised participant sampling approach was used. Extensive exclusion criteria were adopted to ensure that the results were not confounded by extraneous variables (see below). Consequently, 71 subjects participated in the study (46 males and 25 females) ranging between 21 and 96 years of age (mean 57 years). Participants were divided into the handedness categories based on a laterality quotient (LQ) generated by a revised version of the Edinburgh Handedness Inventory. Participants with a $LQ \geq 30$ were classified RH. Those with a $LQ \leq 20$ were classified LH, and those with a LQ between 21 and 29 were classified ambidextrous. This ratio was also used in the original Edinburgh Handedness Inventory.

Patients with congenital anomalies of irregular aortic arch branching patterns were analysed separately to investigate further geometrical abnormalities (providing additional insights into the

nature of the relationship between asymmetrical arteries and handedness). The same applied to participants who had been coerced into changing their hand dominance.

Exclusion criteria. In accordance with normative population findings, one participant fell into the ambidextrous category and was subsequently removed from the study (Thilers et al., 2007). Deceased participants, as well as those who provided inaccurate or outdated contact information, were also excluded. Patients diagnosed with pathological vascular abnormalities of the LC, BT and/or RC (including atherosclerotic disease, arterial stenosis, aneurysm, arterial dissections and other traumatic vascular injuries) were excluded. Any CTA that was incomplete, wrongly formatted, or unclear, were removed. These criteria accounted for the exclusion of 52 participants.

Materials

CTA Scanning. CTA scans were performed using 64 Detector/Slice Toshiba Multidetector CT scanners at three hospitals in Cape Town.

Revised Edinburgh Handedness Inventory. Handedness was assessed using a telephonic administration of a revised version of the Edinburgh Handedness Inventory (Appendix A and B), one of the most popular pencil and paper tests developed for handedness classification (White & Ashton, 1975). Scores obtained from this inventory formed a participant specific LQ, which ranged from 0 (all left) to 50 (all right) to form a LQ (Oldfield, 1975). This version of the inventory does not provide the option of placing a double score for extreme handedness and does not allow indifferent subjects to place a score in both the right and the left columns (Oldfield, 1975). These adaptations address common scoring criticisms of the traditional Edinburgh Handedness Inventory (Oldfield, 1975; Williams, 1991).

Imaging software. RadiAnt DICOM Viewer (64-bit) imaging software was used for the geometric analysis of the arteries.

Procedure

CTA Scanning. Standard medical procedure was followed during CTA scanning — taking approximately 10 seconds each. All source data was stored on a server at the hospital, from which it was accessed via a picture archive and imaging system.

Administration of Handedness Inventory. Interviews were conducted by the author — who remained blind to the nature of the respective CTA scans. Each interview lasted approximately 7 minutes and were conducted predominantly in English (Appendix A). Afrikaans was spoken in instances where participants were not English speaking (Appendix B). Participants were asked whether they were pressured into changing their handedness at a young age. Each interview followed the same procedure. Scores were recorded, an LQ was calculated, and participants were grouped accordingly.

Image processing and vessel analysis. The source CTA data for the participants was imported into a workstation running the Vitrea Core software V.6.2.1 (Vital Images). Using the software's vascular package, a three-dimensional model of the cerebral vasculature with automated removal of the bone and soft tissues was generated. This data was then imported into RadiAnt DICOM Viewer (64-bit) imaging software, where geometric analyses of the relevant arteries were performed — the author remained blind to the identity and LQ of each participant throughout these analyses.

Length. The proximal and distal ends of the vessels under evaluation were manually selected. The proximal end was identified within 3 mm of the start of the vessel and the distal end was identified within 3 mm of the vessel terminus. The length of the LC and the full length of the RC-BT complex, between the proximal and distal ends (in mm), were then obtained (performed in the coronal and sagittal planes). The longest of these measurements for the LC and the RC-BT complex were recorded to ensure that the true length of each vessel was documented — given that one-dimensional CTA vessel length measurements are commonly misguided by angle deviations of the vessel (Kanitsar, Wegenkittl, Fleischmann, & Groller, 2006).

Diameter and area. The proximal and distal parameters established in the length analysis were used to establish the outer boundaries of the diameter and area dimensions for the LC and the RC-BT complex. The vessels' relevant 25th, 50th, and 75th percentile lengths were calculated. Vessel diameter (mm) and area (mm²) were measured at each marker: (1) distal end, (2) 25th percentile, (3) 50th percentile, (4) 75th percentile, and (5) the proximal end of the vessel. Two diameter readings were made at each of these five markers, consisting of the longest and shortest lumen diameter. The means of these two diameters were calculated to ensure that the shape of the vessel lumen did not skew the data. Area was recorded with the specialised tool of the RadiAnt DICOM Viewer. These analyses were conducted in axial view. Maximum and minimum diameters, and areas of these measurements, were selected for further analysis. Mean diameters were excluded from the results as they were skewed by the larger diameter of the BT.

Angle. Two categories of vessel angles were measured. Firstly, the extent to which the vessels deviated from the vertical (the most direct path to the brain) was measured by constructing a vertical line in the RadiAnt DICOM Viewer. A centre line was obtained along the longitudinal axis of the blood vessel. Each instance of angle deviation from this vertical was recorded (in the coronal and sagittal planes), including the angle to which the arteries bifurcated off the aortic arch — deviations of less than 5° were excluded, as this deviation has negligible effects on blood flow (Staalsen et al., 1995). The values were then combined to quantify the total accumulative angle deviation and mean angle deviation of the two vessels, while ensuring that the true three-dimensional deviation of each vessel was documented.

Secondly, the mean artery angles of the vessels were calculated. A vertical line and a centre line were constructed along the longitudinal axis of the blood vessels at each instance of curvature. The angle of this curvature was measured in the coronal and sagittal planes. This was done throughout each of the vessels and included the curvature of the straightest component of each vessel. Mean values for the LC and the RC-BT complex were calculated. Given the nature of this

measurement, the closer the mean vessel angle was to 180°, the straighter it was and therefore the less resistance to blood flow it would cause.

Resistance to blood flow. In order to account for the strong influence of diameter on resistance to blood flow (to the fourth power), Poiseuille's formula was used to calculate the overall resistance of the two vessels of interest (Iordache & Remuzzi, 1995).

$$R_x = \frac{\eta \cdot L}{D^4}$$

Although this model applies to non-curved vessels, the carotid arteries are considered straight enough to justify the assumption of fully developed blood flow in Poiseuille's formula (Iordache & Remuzzi, 1995). No data was available concerning the blood viscosity (η) of the participants, so normative values were used. At 37°C, normative blood viscosity is said to range from 3 to 4x10⁻³ Pa.s (Rosenson, McCormick, & Uretz, 1996). A blood viscosity of 3.5x10⁻³ Pa.s was therefore assumed.

Analysis

Data was analyzed using the Statistica (version 10) software package. The intention was to run a discriminant function analysis (DFA) to differentiate RH and LH vessel geometries and identify significant predictor variables of handedness (Cooley & Lohnes, 1971). The independent variables were the geometric predictors and the dependent variables were the handedness groups. Prior to analysis, the predictor variables were inspected to ensure that the assumptions of DFA were upheld (Klecka, 1980). The data set violated these assumptions. Although unequal sample sizes are acceptable in DFA, the sample size of the smallest group is required to exceed the number of predictor variables. It is recommended that this sample includes at least 20 data sets (William, 1980). The sample size of the LH did not meet this criterion.

Furthermore, assumptions of non-multicollinearity were violated because many of the independent variables were highly correlated with one another. Therefore, the discriminant function

coefficients would not reliably assess the relative importance of the predictor variables (William, 1980).

Independent *t*-tests were therefore used to compare the differences between the geometric variables of participants in the two handedness groups. Comparisons between the LC and the RC-BT complex within each handedness group were also made. Normality tests, namely the Shapiro-Wilk, Kolmogorov-Smirnov, and Lillifors were run on each data set. If assumptions of normality were not upheld, a non-parametric Mann-Whitney test was run instead. Sample specific descriptive statistics of age, race, sex, and handedness were also included.

Asymmetrical branching patterns were identified and removed from the main analysis. These were individually compared to data obtained from participants with conventional branching patterns. The same was done for RH participants who were compelled to use their right hand as a child.

Ethical Considerations

Ethical approval was granted by the University of Cape Town and by all nine branches of the radiology practice in Cape Town. Informed consent was obtained from each subject prior to participation and analysis of the CTA scans (Appendix C and D). Information obtained from the analysis was used solely for the study, and was kept confidential. The participants were informed of the purpose of the research, and assured that their involvement was voluntary and that they could withdraw from the interview at any stage without negative repercussions. Participants were informed that in the event of the author discovering a previously undetected anatomical abnormality during the CTA analysis, confidentiality might be broken, and the relevant hospital would contact the participant, disclose the abnormality, and discuss possible treatments. Debriefing was offered to all participants. There were no overt risks or immediate benefits to the participants.

Results

Of the 71 CTAs analysed, 62 were RH (87.32%) and 8 LH (11.27%) (Table 1). Eleven patients with congenital anomalies involving irregular aortic arch branching patterns were identified. These abnormalities involved the “bovine arch” (n = 9; 12.85%), and an aberrant RS artery (n = 2; 2.86%). Six individuals (9.86%) reported social pressure to change their hand dominance.

Table 1

Descriptive statistics for participants as a function of handedness

	Right-Handed	Left-Handed	Ambidextrous
Age			
Mean age (SD)	67.38 (16.99)	50.25 (11.72)	67
N			
N _{Male}	38	7	1
N _{Female}	24	1	0
N _{Total}	62	8	1
Branching pattern			
Normal	51	8	1
“Bovine arch”	8	0	0
Aberrant RS	2	0	0
Forced handedness	1	5	0

Coronal, sagittal, and axial views of the CTAs of one RH and one LH participant with normal aortic branching patterns visually illustrate the geometric variability of the LC and the RC-BT complex (Figure 3 and 4).



Figure 3. Coronal, sagittal, and axial projection from contrast-enhanced CTAs of LC and the BT-RC complex of one RH participant with a normal branching pattern

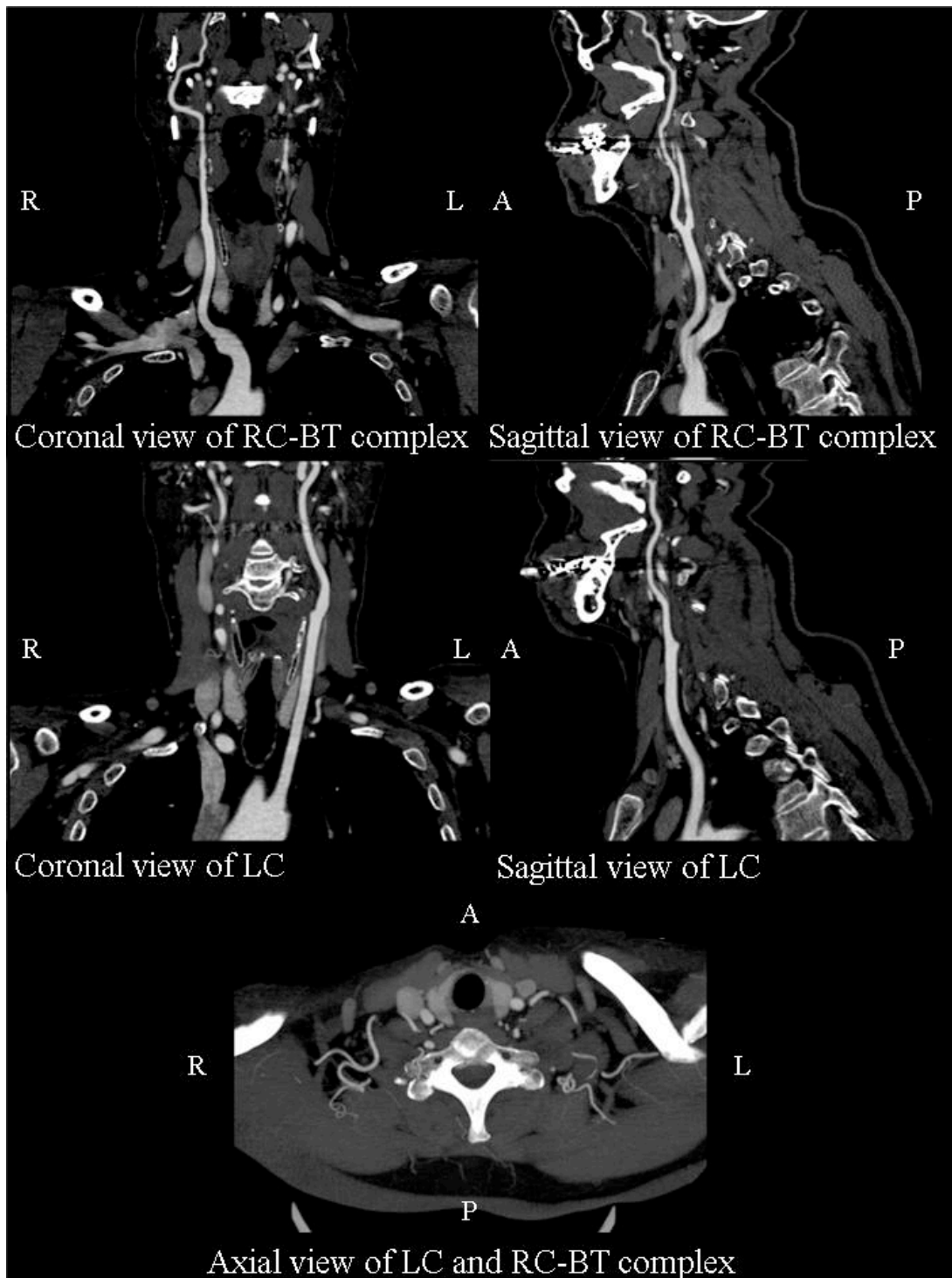


Figure 4. Coronal, sagittal, and axial projection from contrast-enhanced CTAs of LC and the BT-RC complex of one LH participant with a normal branching pattern

Length

Length comparisons between the LC and the RC-BT complexes of LH and RH participants revealed some asymmetries (Table 2). The RC-BT complex ($M = 133.09\text{mm}$, $SD = 14.51$) was

significantly longer than the LC ($M = 122.66\text{mm}$, $SD = 14.63$) in the RH individuals, $t(96) = -3.55$, $p < .001$. This length difference was not significant in LH participants, $t(13) = -0.854$, $p = .408$.

Although lengths of the RC-BT complex were similar in RH and LH participants ($M = 133.95\text{mm}$, $SD = 15.34$), the LC lengths in LH ($M = 127.64\text{mm}$, $SD = 12.91$) were longer than those in RH participants, potentially indicating that LC resistance to blood flow is greater in LH individuals than in RH individuals. However, significance testing did not confirm these differences $t(54) = 0.85$, $p = 0.4$ (Table 3 and 4).

Table 2

Intra comparisons of the geometric properties between the LC and the RC-BT complex of LH and RH participants

Comparisons	Mean (LC)	STDEV (LC)	Mean (RC-BT)	STDEV (RC-BT)	t-value	df	p- value	Cohen's d
Length (mm)								
LH	127.64	12.91	133.95	15.34	-0.85	13	0.409	0.45
RH	122.66	14.63	133.10	14.51	-3.55	96	0.001	0.71
Min Diameter (mm)								
LH	6.43	0.89	7.39	0.90	-2.08	13	0.058	1.07
RH	6.71	0.86	6.43	0.91	1.50	94	0.136	0.32
Max Diameter (mm)								
LH	10.49	1.71	14.91	1.64	-5.09	13	0.000	2.64
RH	10.00	2.45	13.18	1.78	-7.28	94	0.000	1.49
Min area (mm²)								
LH	0.33	0.10	0.43	0.12	-1.94	13	0.074	0.91
RH	0.35	0.09	0.33	0.10	1.05	94	0.297	0.21
Max area (mm²)								
LH	0.84	0.32	1.71	0.43	-4.44	13	0.001	2.30
RH	0.82	0.31	1.38	0.51	-6.61	94	0.000	1.33
Accumulated angle deviation (°)								
LH	156.78	69.27	235.81	96.15	-1.80	13	0.095	0.94
RH	149.50	66.79	238.29	93.09	-5.53	100	0.000	1.10
Mean angle deviation (°)								
LH	23.97	7.02	33.12	9.31	-2.12	13	0.053	1.11
RH	22.78	7.16	30.89	9.08	-5.00	100	0.000	0.99
Mean artery angle (°)								
LH	151.61	14.12	140.80	12.25	1.59	13	0.136	0.82
RH	155.77	10.73	143.65	14.30	4.84	100	0.000	0.96

<i>Resistance (dyn.s.cm⁻⁵)</i>								
LH	0.000314	0.000194	0.000182	0.000116	1.54	12	0.149	0.84
RH	0.000253	0.000156	0.000344	0.000280	-1.99	94	0.053	0.40

Note. $p < .1$

Table 3

Comparisons of the geometric properties of the LC and the RC-BT complex between LH and RH participants

Comparisons	<i>t</i>-value	Df	<i>p</i>-value	Cohen's <i>d</i>
<i>Length (mm)</i>				
LC	0.85	54	0.397	0.36
RC-BT complex	0.15	55	0.879	0.06
<i>Min Diameter (mm)</i>				
LC	-0.79	53	0.431	0.32
RC-BT complex	2.74	54	0.008	1.06
<i>Max Diameter (mm)</i>				
LC	0.69	53	0.491	0.23
RC-BT complex	1.92	54	0.060	1.01
<i>Min area (mm²)</i>				
LC	-0.45	53	0.654	0.21
RC-BT complex	2.87	54	0.006	0.91
<i>Max area (mm²)</i>				
LC	-0.19	53	0.847	0.06
RC-BT complex	1.74	54	0.088	0.70
<i>Accumulated angle deviation (°)</i>				
LC	0.27	56	0.789	0.11
RC-BT complex	-0.07	57	0.945	0.03
<i>Mean angle deviation (°)</i>				
LC	0.41	56	0.681	0.17
RC-BT complex	0.64	57	0.522	0.24
<i>Mean artery angle (°)</i>				
LC	-0.50	57	0.620	0.33
RC-BT complex	-0.32	58	0.747	0.21
<i>Resistance (dyn.s.cm⁻⁵)</i>				
LC	0.99	53	0.357	0.35
RC-BT complex	-1.50	53	0.139	0.75

Note. $p < .1$.

Table 4

Comparisons of the differences in geometric properties of the LC and the RC-BT complex between LH and RH participants (calculated by RC-BT complex – LC)

Comparisons	Mean (LH)	STDEV (LH)	Mean (RH)	STDEV (RH)	t-value	df	p-value	Cohen's d
Length (mm)	6.37	6.63	10.03	8.26	-1.12	56	0.267	0.49
Min Diameter (mm)	1.54	2.21	-0.27	0.63	4.88	55	0.000	1.11
Max Diameter (mm)	5.73	3.64	3.18	1.88	3.05	54	0.004	0.88
Min area (mm ²)	0.15	0.13	-0.02	0.08	4.96	54	0.000	1.58
Max area (mm ²)	0.98	0.43	0.56	0.38	2.77	54	0.008	1.04
Accumulated angle deviation (°)	99.06	67.17	88.78	60.66	0.42	56	0.680	0.16
Mean angle deviation (°)	10.46	5.06	8.10	6.48	0.92	56	0.360	0.41
Mean artery angle (°)	-14.01	8.41	-12.13	9.77	2.22	56	0.630	0.21
Resistance (dyn.s.cm ⁻⁵)	-0.000132	0.000113	0.000091	0.000169	-3.37	53	0.001	1.38

Note. $p < .1$

Diameter and Area

Diameter comparisons between the LC and the RC-BT complexes and between LH and RH participants revealed significant asymmetries.

Minimum. In LH participants, minimum RC-BT complex diameters ($M = 7.39\text{mm}$, $SD = 0.90$) were statistically larger than LC diameters ($M = 6.43\text{mm}$, $SD = 0.89$), $t(13) = -2.08$, $p = .058$, $d = 1.07$. The reverse was true for RH participants: LC minimum diameters ($M = 6.71$, $SD = 0.86$) were larger than RC-BT complex diameters ($M = 6.43\text{mm}$, $SD = 0.91$). This asymmetry tended towards statistical significance $t(94) = 1.50$, $p = .14$. The asymmetry in diameters was mirrored by area values (Table 2).

In addition, minimum diameters of the BR-RC complex were statistically greater in LH participants than in RH participants, $t(54) = 2.74$, $p = .008$. Cohen's effect size value ($d = 1.06$) suggests a high practical significance of this difference. Although minimum LC diameters were greater in RH subjects, this was not significant $t(53) = -0.79$, $p = .43$, $d = 0.32$. The same pattern was established in area values (Table 3).

Investigating the asymmetries in minimum diameter differences of the LC and the RC-BT complex yielded another inverse relationship: LH individuals had a positive mean difference ($M = 1.54\text{mm}$, $SD = 2.21$), RH participants had a negative mean difference ($M = -0.27\text{mm}$, $SD = 0.63$). This asymmetry was significant, $t(55) = 4.88$, $p < .001$, and Cohen's effect size value ($d = 1.11$) suggests a high practical significance. This was further supported by similar significant findings in recorded vessel areas (Table 4).

Maximum. Maximum RC-BT complex diameters in LH ($M = 14.91$, $SD = 1.64$) and RH participants ($M = 13.18\text{mm}$, $SD = 1.78$) were greater than their respective LC diameters ($M = 10.49\text{mm}$, $SD = 1.71$; $M = 10.00\text{mm}$, $SD = 2.45$). For LH, this was a statistical significance of $t(13) = -5.08864$, $p < 0.001$. For RH there was a significance value of $t(94) = -7.27715$, $p < .001$ (Table 2).

The maximum diameters of the LC were of similar size in both LH and RH participants $t(53) = 0.693995$, $p = 0.49$. However, maximal diameters of the RC-BT complex were significantly greater in LH individuals, $t(54) = 1.92$, $p = .06$, $d = 1.01$ (Table 3).

There was a significant asymmetry in maximum vessel diameter differences between LH and RH subjects (Table 4). There was a statistically greater difference in maximum diameters in LH subjects ($M = 5.73\text{mm}$, $SD = 3.64$) than in RH ones ($M = 3.18\text{mm}$, $SD = 1.88$), $t(54) = 3.047509$, $p = .003$. Furthermore, Cohen's effect size value ($d = 0.88$) suggests a high practical significance of this difference. The same findings were repeated for area geometries.

Angle Measurements

There were significant asymmetries of vessel angles between the LC and the RC-BT. These asymmetries were found in accumulative angle deviation, mean angle deviation, and mean artery angle.

Angle deviation from 90°. Measurements of accumulative and mean angle deviation from 90° consistently revealed that the RC-BT complex had a significantly greater degree of curvature

than the LC in both RH ($t(100) = -5.53, p < .001$) and LH individuals ($t(13) = -1.80, p = .09$).

Interestingly, LC accumulative angle deviations were greater in LH participants ($M = 156.77^\circ, SD = 69.27$) than in RH participants ($M = 149.50^\circ, SD = 66.79$) suggesting a greater degree of blood flow disturbance in the LC. Likewise, RC-BT complex angle deviations were greater in RH participants ($M = 238.29^\circ, SD = 93.08$) than in LH participants ($M = 235.81^\circ, SD = 96.7$). Neither of these findings was statistically significant. These findings were mirrored in the mean angle deviation measurements (Table 2).

Mean artery angle. The mean artery angles of the two vessels reflected similar asymmetries to those established for artery angle deviation from 90° . The RC-BT complex had a significantly greater degree of curvature than the LC in RH individuals ($t(100) = 4.84, p < .001$). This difference was not as apparent in LH individuals ($t(13) = 1.59, p = .14$). Interestingly, the LC had a greater curvature in LH participants ($M = 151.61^\circ, SD = 14.12$) than in RH participants ($M = 155.77^\circ, SD = 10.73$). Likewise, the RC-BT complex was more curved in RH participants ($M = 143.65^\circ, SD = 14.30$) than in LH participants ($M = 140.79^\circ, SD = 12.25$). These findings were not statistically significant.

Resistance to blood flow

The calculated resistance to blood flow of the two vessels showed that the RC-BT complex had a significantly greater degree of resistance than the LC in RH individuals, $t(94) = -1.96, p = .05, d = 0.40$. This difference was not significant in LH individuals $t(12) = 1.54, p = .15$. Interestingly, the LC had a greater resistance in LH participants ($M = 0.000314 \text{ dyn.s.cm}^{-5}, SD = 0.000194$) than in RH participants ($M = 0.000253 \text{ dyn.s.cm}^{-5}, SD = 0.000156$). However, this was not significant. Correspondingly, the RC-BT complex had a greater degree of resistance in RH individuals ($M = 0.000344 \text{ dyn.s.cm}^{-5}, SD = 0.000280$) than in LH individuals ($M = 0.000182 \text{ dyn.s.cm}^{-5}, SD = 0.000116$). This finding tends towards significance, $t(53) = -1.503, p = 0.14, d = 0.75$.

Investigating the asymmetries in blood flow resistance differences of the LC and the RC-BT complex yielded a significant difference. While RH individuals had a positive mean difference in resistance ($M = 0.000091 \text{ dyn.s.cm}^{-5}$, $SD = 0.000169$), LH participants had a negative mean resistance difference ($M = -0.000132 \text{ dyn.s.cm}^{-5}$, $SD = 0.000113$). This asymmetry was significant, $t(53) = -3.37$, $p = .001$. Cohen's effect size value ($d = 1.38$) suggested a high practical significance of this asymmetry, showing that in RH participants, the RC-BT complex had greater blood flow resistance than the LC, while in LH participants it had less resistance than the LC (Table 4).

Forced Handedness

One RH (1.40%) and 5 LH (7.04%) reported early pressure to change their handedness. Although this means that only 1.61% of the RH participants were subjected to this social pressure, a total of 62.5% of LH were coerced (unwillingly) to change their handedness. Reclassifying the 'switched' RH participant into the LH category produced insignificant changes to the results, the only notable alteration being that the asymmetrical blood flow resistance of the RC-BT complex between RH and LH participants became significant $t(53) = -1.72$, $p = .09$.

Including the ambidextrous participant in the LH group produced little change to the findings. The minimum diameter of the RC-BT complex was still larger than the LC for LH individuals. However, this difference was no longer significant $t(15) = -1.62$, $p = .13$; due to the fact that the minimum diameter for the LC (7.55mm) was larger than the RC-BT (7.30mm) complex in the ambidextrous individual — the inverse of what was found in the main analysis.

Similarly, although the RC-BT complex was still more curved than the LC with the inclusion of the ambidextrous participant, the accumulative angle deviation between these vessels in LH participants was no longer significant, $t(15) = -1.72$, $p = 0.11$.

Alternate branching patterns

Eleven patients with congenital anomalies of aortic arch branching patterns were identified. These anomalies involved cases of the “bovine arch” (n = 9) (Figure 4), and an aberrant RS (n = 2) (Figure 5). All of these participants were RH.

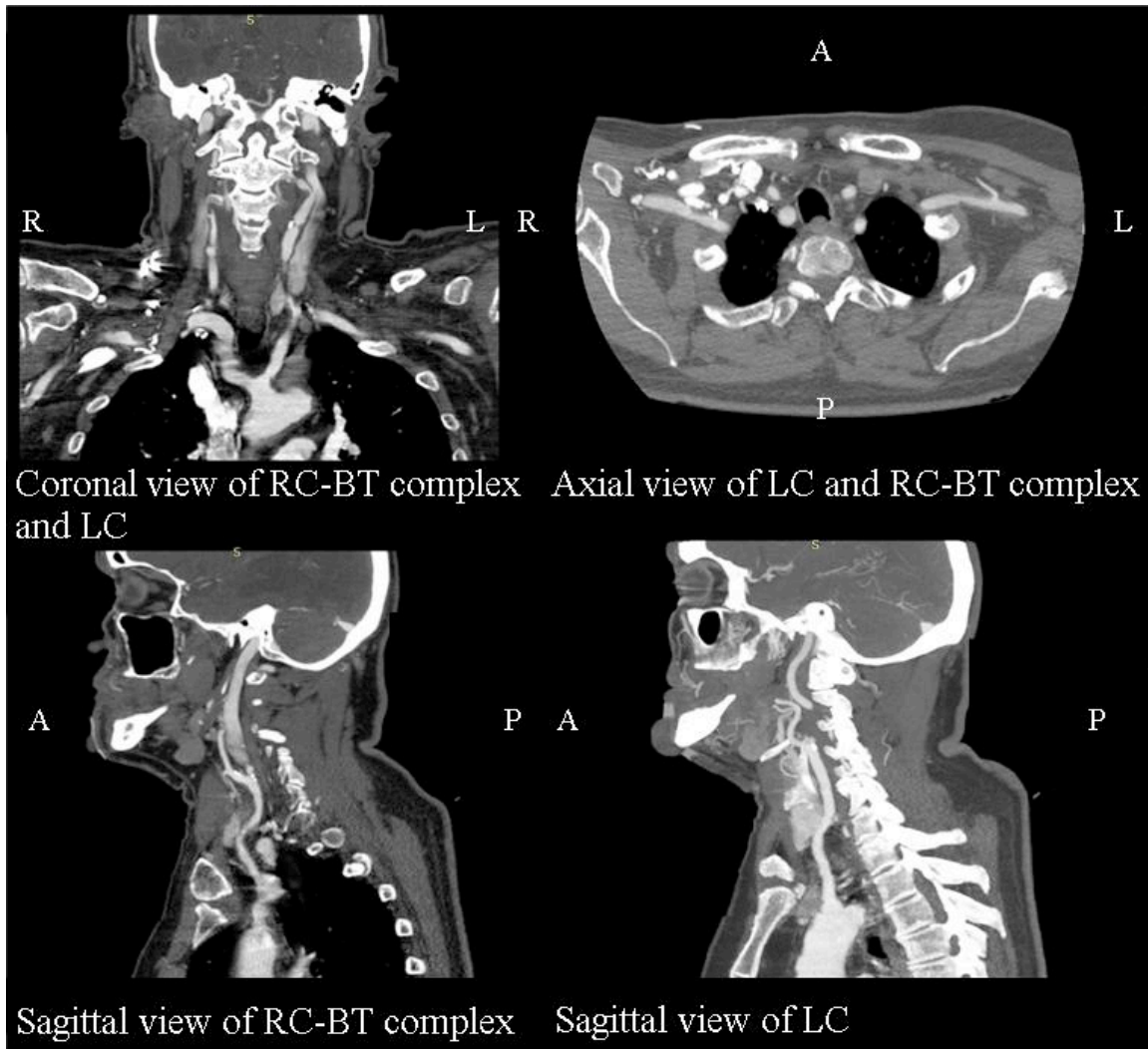


Figure 5. Coronal, sagittal, and axial projection from contrast-enhanced CTAs of LC and the BT-RC complex of one RH participant with an abnormal branching pattern (“bovine arch”)

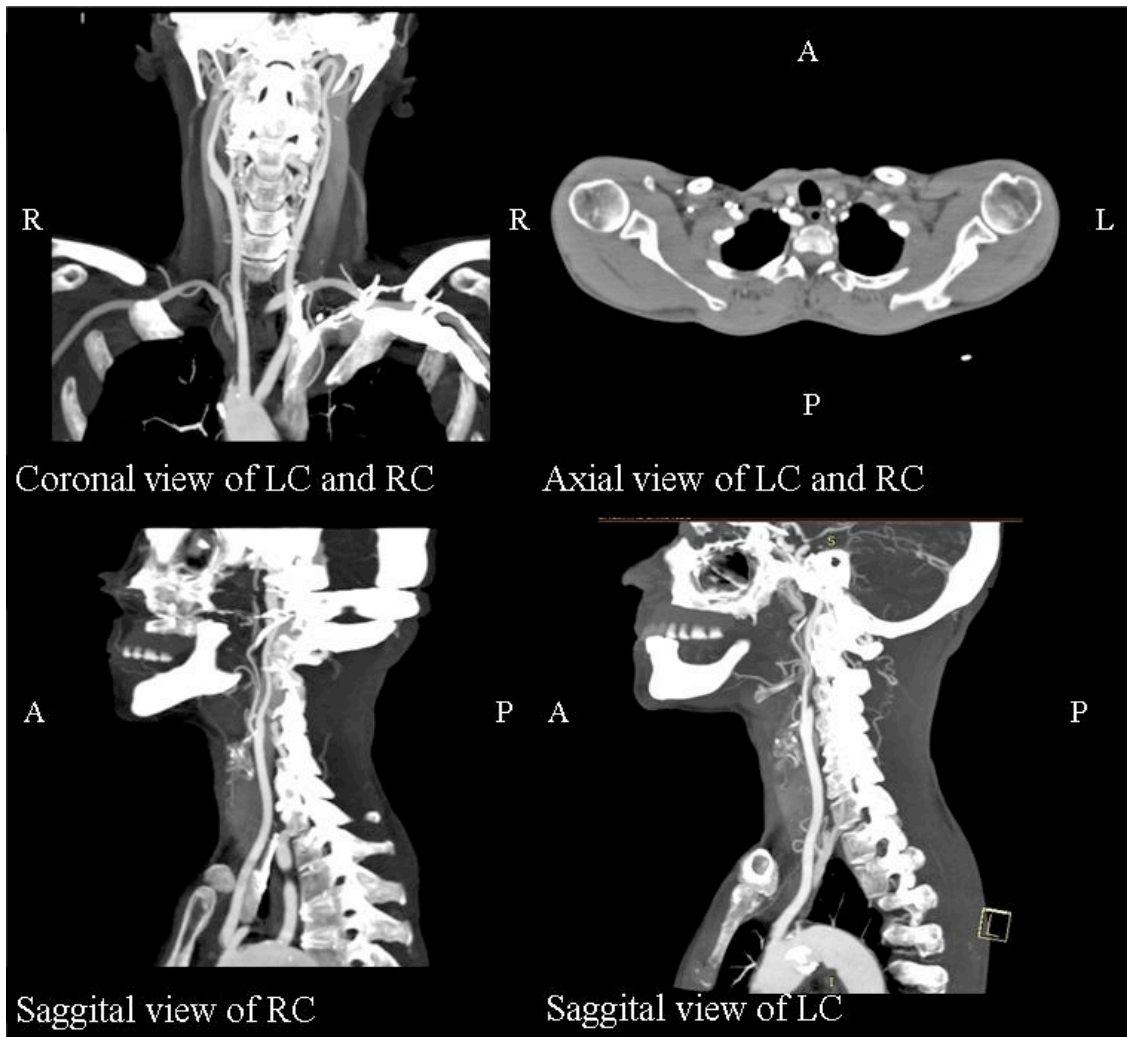


Figure 6. Coronal, sagittal, and axial projection from contrast-enhanced CTAs of LC and RC of one RH participant with an abnormal branching pattern (aberrant RS)

Bovine arch. It is clear that a number of geometric differences existed between the aortic branches of a normal branching pattern and those of a “bovine arch” (Table 5). No significant differences in length and mean angle deviation were found. Due to the nature of the abnormal branching pattern where the LC and the RC share a common origin, the maximum diameters of both vessels were the same ($M = 16.99$, $SD = 2.79$). These were significantly larger than the maximum diameters of the LC ($t(54) = 10.09$, $p < .001$) and the RC-BT complex ($t(54) = 4.36$, $p < 0.001$) of normal branching patterns. Further differences were found in minimum diameter. In participants with a common BT, the minimum diameters of both the LC ($M = 6.17$, $SD = 1.21$) and the RC ($M = 5.69$, $SD = 1.19$) were smaller than those with a normal branching pattern. While this

difference in LC diameter tended towards significance, $t(54) = -1.54, p = 0.13$, differences in the RC-BT complex were significant, $t(54) = -2.06, p = .045$.

Accumulative angle deviation of the RC-BT complex ($M = 299.27, SD = 150.41$) was significantly higher in individuals with a common BT, $t(57) = 1.69, p = 0.09$. All these findings indicate that individuals with a common BT had an overall higher resistance to blood flow, with a particular increase in the resistance in the RC-BT complex. Calculated resistance to blood flow supported these findings. Both the LC ($M = 0.000497, SD = 0.000663$) and the RC-BT complex ($M = 0.000792, SD = 0.001097$) had a significantly higher resistance to blood flow than normal branching patterns: $t(54) = 2.26, p = 0.03$ and $t(54) = 2.46, p = 0.01$ respectively.

Table 5.

Geometric properties	Mean (BA)	STDEV	Mean (N)	STDEV (N)	t-value	df	p-value
Length (mm)							
LC	125.36	21.43	122.65	14.78	0.47	55	0.64
RC-BT complex	134.71	22.27	133.02	14.66	0.29	55	0.77
Min Diameter (mm)							
LC	6.17	1.21	6.68	0.85	-1.54	54	0.13
RC-BT complex	5.69	1.19	6.40	0.90	-2.06	54	0.045
Max Diameter (mm)							
LC	16.99	2.79	9.99	1.73	10.09	54	0.000
RC-BT complex	16.99	2.79	13.09	2.40	4.36	54	0.000
Accumulated angle deviation (°)							
LC	182.26	83.74	145.72	61.70	1.55	57	0.13
RC-BT complex	299.27	150.41	236.39	93.03	1.69	57	0.09
Mean angle deviation (°)							
LC	25.60	9.01	22.49	6.91	1.19	57	0.24
RC-BT complex	33.51	11.51	30.39	8.45	0.96	57	0.34
Mean artery angle (°)							
LC	150.16	10.81	156.26	10.25	-1.63	57	0.11
RC-BT complex	142.30	13.45	144.50	13.07	-0.46	57	0.65
Resistance (dyn.s.cm⁻⁵)							
LC	0.000497	0.000663	0.000256	0.000156	2.26	54	0.03
RC-BT complex	0.000792	0.001097	0.000349	0.00028	2.46	54	0.01

Note. $p < .1$; BA = Bovine arch; N = Normal

Comparisons of the geometric properties of the LC and the RC-BT complex between normal and “bovine arch” branching patterns of RH participants

Aberrant RS. Only 2 participants showed an aortic arch branching abnormality where no BT was present, causing the RC to originate directly off the aortic arch. Due to the small number in this group, no statistical analyses could be run. Despite this, some interesting results were observed. The lengths of the LC ($M = 133.35$, $SD = 8.70$) and the RC ($M = 132.35$, $SD = 14.79$) become almost indistinguishable in individuals with no BT due to an increased LC length. Similarly, the minimum diameter of the LC ($M = 6.05$, $SD = 1.20$) and the RC ($M = 6.08$, $SD = 0.74$), and the maximal diameter of the LC ($M = 8.05$, $SD = 1.34$) and the RC ($M = 7.63$, $SD = 0.04$), were alike, and were smaller than those with normal branching patterns. This predicts a higher, yet more even resistance to blood flow between the two vessels, which is supported by resistance to blood flow calculations.

However, there was a large angle asymmetry between the two vessels that was not apparent in RH participants with normal aortic arch branching patterns. Although the accumulative angle deviation of the LC was larger ($M = 156.45$, $SD = 97.93$) than that of normal RH participants, the deviation of the RC was substantially greater ($M = 300.45$, $SD = 249.82$). This was further supported by a much higher RC mean angle deviation ($M = 36.24$, $SD = 16.23$), and much lower mean artery angle ($M = 137.14$, $SD = 33.76$). This potentially compensates for the lack of geometric asymmetry of the other geometric variables.

Table 6.

	Length (mm)	Min Diameter (mm)	Max Diameter (mm)	Accumulative angle deviation (°)	Mean angle deviation (°)	Mean artery angle (°)	Resistance ($dyn.s.cm^{-5}$)
LC (SD)	133.35						0.0004320
	(8.70)	6.05 (1.20)	8.05 (1.34)	156.45 (97.93)	22.83 (7.62)	156.87 (12.08)	(0.00033)
	132.35	6.08 (0.74)	7.63 (0.04)	300.45 (249.82)	36.24 (16.23)	137.14 (33.76)	0.0003758

<i>RC-BT complex (SD)</i>	132.35 (14.79)	6.08 (0.74)	7.63 (0.04)	300.45 (249.82)	36.24 (16.23)	137.14 (33.76)	0.0003758 (0.00021)
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LC and RC geometric properties of RH participants with and aberrant RS artery.

The inclusion of participants with both forms of alternate branching in the main analysis resulted in only a few notable changes to the findings. As expected, the maximum diameters of the RC-BT complex were no longer significantly different between LH and RH participants $t(66) = 1.25, p = .22$. Not only was the minimum diameter of the RC-BT complex significantly larger in LH than in RH participants, but this was statistically stronger than in the main analysis $t(66) = 3.00, p = .003$. Furthermore, the inverse of this relationship also became significant: the minimum diameter of the LC was significantly larger in RH than in LH participants, $t(65) = 2.46, p = .01$. This verifies the inverse relationship identified in the main analysis. Although differences in resistance to blood flow of the RC-BT complexes between LH and RH individuals tended towards significance, the findings of the new analysis made this difference statistically significant. Consequently, the RC-BT complex was significantly greater in RH than in LH individuals $t(64) = 2.47, p = .008$.

Discussion

Functional magnetic resonance imaging studies show that handedness reflects a hemispheric asymmetry during the planning and performance of complex motor sequences (Haaland et al. 2004). While RH participants have increased blood flow in the left hemisphere in order to satisfy the increased metabolic activity, LH individuals are more active in the right hemisphere (Vivani et al., 1998). Given that large arteries regulate cerebral blood flow, an investigation of the geometry of the large arteries that supply the brain for the location of blood flow asymmetries is essential (Magun, 1973).

Results provide evidence confirming the main research hypothesis. The analysis revealed considerable asymmetries between the geometric properties of the LC and RC-BT complex. Further differences between LH and RH participants indicate an increased blood flow resistance on the side

contralateral to the dominant hemisphere. Left-handed subjects demonstrated increased blood flow resistance in the LC, while RH participants showed higher blood flow resistance in the RC-BT complex. This was evident in the variables of minimum diameter and calculated resistance to blood flow, and is validated by the high effect sizes.

Right-handers comprised 87.32% of the participants, while 11.27% were LH, and 0.01% were ambidextrous; numbers that reflect established handedness norms (Rife, 1940; Oldfield, 1971, Thilers et al., 2007). This sample also accords with normative sex-related data, as over 80% of the LH participants were male (Vuoksimaa et al., 2009). The sample was representative of a wide range of age groups (from 21 to 96 years, mean age of 57 years). This controlled for the influence of empirically established age related changes in the structure and function of the cardiovascular system such as progressive dilatation and elongation of major arteries, arterial wall thickening, and arterial stiffness (Oxenham & Sharpe, 2003).

Conventional branching patterns

A conventional branching pattern was found in the majority of the participants (84.28%), consistent with the normative findings of Alsaif and Ramadan (2010), and Jakanani and Adair (2010). The mean arterial length of the LC in RH participants corresponds to the normative geometric measurements of Avolio (1980). Due to this study's unique assessment of the RC-BT complex (rather than analysing RC in isolation), no further comparisons could be made with normative data regarding these vessels. Although lengths of the RC-BT complex were similar in RH and LH participants, LC lengths were longer in LH participants. This asymmetry was not statistically significant, but indicates that LC resistance to blood flow is potentially greater in LH individuals than in RH individuals.

Multiple diameters and areas were measured throughout each of the vessels to form minimum, mean, and maximum diameter measurements. Mean diameters and areas were, however,

excluded from the results because they were skewed by the larger diameter of the BT and therefore provided no accurate indication of comparative arterial blood flow.

Minimum diameters and areas of the RC-BT complex were statistically greater in LH participants than in RH participants. Due to the considerable influence that luminal diameter has on blood flow, this disparity indicates substantially greater amounts of blood flow through the RC-BT complex (Iordache & Remuzzi, 1995). The converse was true for RH participants, as minimum LC diameters and areas were larger than those in the RC-BT complex. Although this was not significant in the main analysis, a second analysis (including all branching variations) defined this difference as significant.

Comparing the minimum diameter differences of the LC and the RC-BT yielded another significant inverse relationship. When LC values are subtracted from RC-BT values, LH individuals demonstrated a positive mean difference while RH participants showed a negative mean difference. This is consistent with the study hypotheses, as the difference in minimum diameter between the two vessels discloses a significant asymmetry contralateral to handedness. This contradicts the findings of Manbachi et al. (2011) who used a small sample size, failed to investigate minimum diameters, neglected BT, and made no comparisons to LH individuals. These findings confirm those of Onbas et al. (2007) who demonstrated higher hemodynamic stress and intimal damage in the LC of RH compared to LH individuals.

It is known that the maximum diameter of the BT, located at its origin, is larger than the maximum diameter of the LC (Alsaif & Ramadan, 2008; Shin et al., 2008). This study confirms this asymmetry, and is in accordance with Alsaif and Ramadan (2008) and Shin et al. (2008). However, although the maximum diameters and areas of the LC were of similar size in both the LH and the RH participants, the maximum diameters and areas of the RC-BT complex were significantly greater in the LH individuals. This supports the study's hypothesis, pointing to higher blood flow volumes entering the RC-BT complex from the aortic arch in LH versus RH individuals. This is

further supported by the statistically larger difference in maximum diameters between the vessels of the LH subjects versus those of the RH subjects.

Shin et al. (2008) conclude that the average angles at which the major branches arise from the aortic arch are much larger in the BT than in the LC. Although angle deviations at the origin of the aortic arch were not investigated in isolation here, it has been consistently established that the RC-BT complex has a significantly greater degree of curvature than the LC in both RH and LH individuals. However, each angle measure established greater LC curvature in LH participants than in RH participants, suggesting a greater blood flow disturbance in the LC for LH than for RH participants. Likewise, RC-BT complex curvature is greater in RH participants than in LH participants. Although these findings are not statistically significant, they are consistent with this study's hypotheses. This contradicts the findings of Manbachi et al. (2011) who argue that the LC is more curved than the RC. However, Manbachi et al. (2011) did not take the angles of the BT into account in their arterial analysis, therefore, an accurate comparison cannot be made between these findings and those of the present study.

Poiseuille's formula allowed for the calculation of resistance to blood flow for each of the vessels under investigation. Although normative viscosity measures were used throughout the analysis, the reliability of the calculated resistance was not compromised, as there is no reason to suspect that blood viscosity differs between LH and RH individuals. It could be argued that the comparative power of the formula is enhanced in this way, as the calculated resistance to blood flow is determined solely by the relevant geometric measures. Differences in resistance to blood flow of the RC-BT complex between the LH and RH individuals tended towards significance in the main analysis. However, the secondary analysis (including all branching variations) made this difference statistically significant. Furthermore, resistance differences of the LC and the RC-BT complex in the LH and RH participants yielded a significant difference. While RH individuals demonstrated a positive mean difference in resistance, LH participants showed a negative mean resistance difference. This asymmetry is significant, and is consistent with the study hypotheses,

suggesting that the RC-BT complex has consistently greater blood flow resistance than the LC in RH participants. Conversely, the LC consistently has a greater resistance to blood flow than the RC-BT complex in LH participants.

Buxton and Frank (1997) estimate that a flow increase of 19% is required for a 5% increase in localised cerebral oxygen metabolic rate (Kim et al., 1993). This study's findings show that percentage flow increase in the LC is 21.57% higher in RH than in LH individuals. Furthermore, percentage flow increase in the RC-BT complex is 61.56% higher in LH individuals than RH individuals. Consequently, localised cerebral oxygen metabolic rates are approximately 5.7% greater in the left hemisphere of the RH participants, and 16.21% greater in the right hemisphere of LH participants, thereby strongly confirming the research hypothesis. The handedness-related flow rate asymmetries between the right and left internal carotid arteries, established by Bogren et al. (1994), are therefore already apparent in the primary branches of the aortic arch.

It is important to keep in mind that the presence of side branches induces blood flow disturbances, which cause decreased blood flow efficiency. Therefore, the very nature of the conventional branching pattern causes decreased blood flow efficiency in the RC-BT complex. These disturbances only occur at angles greater than 15° (Staalsen et al., 1995). This study did not measure angles of the RC bifurcation independently and therefore cannot draw conclusions regarding the influence of angle bifurcation on the blood flow of the participants.

Ambidextrous. Although the inclusion of the ambidextrous participant in the LH group only marginally influenced the results, some interesting results were observed. The inclusion caused minimum diameter and artery angle differences between the two arteries in LH individuals to lose their significance; however, the minimum diameter for the LC was larger than the RC-BT complex. This follows the same asymmetry pattern found in RH participants, and is further reflected in resistance to blood flow, as the ambidextrous participant had a higher resistance to blood flow in the RC-BT complex than the LC. However, variables of curvature and length reflect the blood flow patterns of the LH participants. Since these differences were not as large as the differences found in

the RH and LH participants, the findings indicate that the arterial geometry of ambidextrous individuals reflected a combination of LH and RH blood flow asymmetries, but to a lesser extent. The small ambidextrous sample dictates cautious in interpretation of these findings.

Since the data set violated many DFA assumptions, no conclusions can be made regarding to the extent to which the above geometric variables predict handedness.

Alternate branching patterns

The frequency of alternative branching patterns confirms the findings of Alsaif and Ramadan (2010), Jakanani and Adair (2010), and Gupta and Sodhi (2005). The most frequent anatomical variant in the present study was a common origin in the LC and RC-BT complex (12.85%), termed the “bovine arch”. Another rare branching abnormality identified was an aberrant RS artery (complete absence of the BT) found in 3.23% of the sample.

Bovine arch. Geometric differences between conventional branching patterns and the “bovine arch” pattern indicated that the arteries had significantly greater overall resistance to blood flow with a particular increase in the resistance in the RC-BT complex. Therefore, a handedness-related bias was still evident. No significant differences in length and mean angle deviation were found. Due to the common origin of the LC and the RC, the maximum diameters at this origin are significantly larger than those in conventional branching patterns. Although this is expected, the increased diameter does not compensate for the area required to maintain normative blood volumes in the vessels. Consequently, initial blood volumes into these vessels will be lower than those of conventional branching patterns. Furthermore, the minimum diameters of both the LC and the RC are smaller than those with a normal branching pattern — this was particularly significant in the RC. Although accumulative angle deviation of the RC-BT complex was significantly higher in individuals with a common BT, the high variability of these findings demands cautious interpretation.

Aberrant RS artery. Only two participants showed an aortic arch branching abnormality where no BT was present, causing the RC to originate directly off of the aortic arch. Despite the inability to run statistical analyses on this small sample, the geometric properties of these vessels indicate a higher and more even resistance to blood flow between the two vessels. This can be seen in the indistinguishably different relative geometric characteristics of length, minimum diameter, maximum diameter, and resistance to blood flow, in individuals with an aberrant RS artery. However, handedness-related blood flow disparity is potentially maintained through increased vessel curvature. There was a large angle asymmetry between the two vessels in comparison to RH participants with conventional branching patterns. The accumulative angle deviation, mean angle deviation, as well as mean artery angle values, indicate that the curvature of the RC is considerably greater than that of the LC. Furthermore, this curvature is substantially greater than the RC-BT complexes of those of normal RH participants. Research has established that mild curvature, as low as 15° , is sufficient to cause significant blood flow disturbances (Banerjee et al., 1992; Manbachi et al., 2011). Therefore, the mean artery angle difference of 19.73° between the RC and the LC artery indicates that a noteworthy flow discrepancy is evident, which potentially compensates for the lack of geometric asymmetry of the other geometric variables in the direction predicted by the participants' handedness. However, the small sample size and high variability of the data decrease the reliability of these claims.

Forced handedness. To investigate potential social and environmental moderators of handedness, participants with potentially 'switched' handedness were specifically included. Only one RH participant consistently experienced social pressure to alter their handedness, while 5 of the LH group were unsuccessfully coerced to alter their hand dominance. This accords with Perelle and Ehrman's (1994) findings that older LH adults reported pressure to become RH from a young age. However, given that statistical analyses could not be performed, no insights have been gained into the role of genetic and environmental factors in human hand preference, leaving the topic of the haemodynamic consequences of handedness conversion remaining unexplored.

Limitations and directions for future research

This study's findings confirm the hypothesis that the geometric characteristics of the LC and RC-BT complex are asymmetrical, and in a direction that promotes blood supply to the respective dominant hemispheres in RH and LH individuals. However, replication using a larger number of LH participants is needed to increase the statistical validity of these findings. Given that this study was prospective in nature, it made use of an existing medical population, rendering the findings not necessarily generalisable to the general population. Future studies should investigate healthy populations that are representative of all races, sexes, and ages — to determine the validity of the significant findings presented here, and show whether the asymmetries that tended towards significance are statistically valid.

This study was based on handedness information acquired from a standardised questionnaire. Given that handedness is best determined by combining subjective preference measures and performance measures, future studies should complement self-reports of handedness with observational measures of hand performance, through tasks such as finger tapping (Brown, Roy, Rohr, & Bryden, 2006).

Furthermore, research should determine the extent to which asymmetrical blood flow influences handedness, as well as the manner in which this asymmetry relates to structural cerebral asymmetries. Since no conclusions of causality could be drawn here, it is important that further research identifies whether the geometric asymmetries of blood vessels result in handedness, or area consequence of hemispheric lateralisation.

Summary and Conclusions

The identification and quantification of asymmetries between the LC and the RC-BT complex provides new insight into a potential anatomical bias in cerebral lateralisation. The

findings presented here provide compelling evidence that RH individuals have dominant LC arteries (21.57% increased flow) that may be considered responsible for approximately 5.7% increased metabolic rate in the left hemisphere. Conversely, LH individuals have dominant RC-BT complex arteries (61.57% increased flow) that would be responsible for an approximately 16.21% increased metabolic rate in the right hemisphere. This is particularly evident in the minimum and maximum arterial diameters, as well as in the calculated resistance to blood flow. These variables showed particularly high effect sizes, thereby validating the practical significance of the findings. This strongly confirms the research hypothesis.

The geometric characteristics of the ambidextrous participant suggest the possible interplay of RH and LH-related asymmetries. The geometric properties of RH alternate arterial branching patterns produced a significantly greater overall resistance to blood flow in both vessels. However, a handedness-related bias was maintained through increased asymmetry of particular geometric properties. While the compensatory geometric characteristic was minimum diameter in participants with a common BT, participants with no BT seemed to be influenced by vessel curvature.

No causal relationship could be concluded from this study. It is therefore not clear whether the arterial geometric asymmetries identified, particularly in minimum vessel diameter, may result in handedness, or whether they are as a result of hemispheric dominance. This key issue that should be addressed by future research.

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Appendix A

Appendix A

Revised Edinburgh Handedness Inventory (English)

Indicate hand preference in the following activities:

	Always left (1)	Usually left (2)	No preference (3)	Usually right (4)	Always right (5)
1. Writing					
2. Throwing a ball					
3. Cutting with scissors					
4. Brushing teeth					
5. Using a knife (without a fork)					
6. Eating with a spoon					
7. Striking a match (match)					
8. Opening a box (lid)					
9. Kicking a ball					
10. Using a computer mouse					

Additional question

11. As a child, were you ever forced to use your right hand to complete tasks, when you were in fact more comfortable using the left? YES/NO

Appendix B

Revised Edinburgh Handedness Inventory (Afrikaans)

Dui jou handvoorkeuraan vir die volgende aktiwiteite:

	Altyd links (1)	Gewoonlik links (2)	Geen voorkeur (3)	Gewoonlik regs (4)	Altyd regs (5)
1. Skryf					
2. 'n Balgooi					
3. Met 'n skêr sny					
4. Tande borsel					
5. Gebruik van 'n mes (sonder 'n vurk)					
6. Eet met 'n lepel					
7. 'n Vuurhoutjie trek					
8. 'n Houer oopmaak (deksel)					
9. 'n Balskop					
10. 'n Rekenaar muis gebruik					

Addisionele vraag

11. Was jy ooit as kind gedwing om jou regterhand te gebruik om take te verrig, terwyl jy in werklikheid gemakliker was om dit met jou linkerhand te doen? JA/NEE

Appendix C

Description of Verbal Consent Process (English)

“Good morning, my name is Anica Jansen van Vuuren. I am a postgraduate student in the Department of Psychology at the University of Cape Town. I am working with a neurologist in Gatesville Medical Centre, Dr Ameen, and together we are doing a study on handedness in South Africa and its possible link to vascular asymmetry of the branches of the aortic arch.

The information you share with me will be of great value in helping me to complete this research project, the results of which could significantly enhance our understanding of the origins of handedness.

This interview will take approximately seven minutes of your time. All information will be strictly confidential. Your data will be stored according to a coding number, so your identity will remain anonymous throughout this research project. Your CTA scans will only be handled by me and medical practitioners. If any previously undetected anatomical abnormalities are found during the CTA analysis, confidentiality may be broken in so far as the neurologist may then discuss the abnormality and possible medical treatment with you. There are no other expected risks of participation.

Participation is voluntary. If you decide not to participate in the study or to withdraw your participation at any time you may do so with no consequences whatsoever.

Do you agree to participate in this study?

...

Thank you.”

Appendix D

Description of Verbal Consent Process (Afrikaans)

“Goeie more, my naam is Anica Jansen van Vuuren. Ek is ‘n nagraadse student in die Departement Sielkunde aan die Universiteit van Kaapstad. Ek werk saam met ‘n neuroloog in Gatesville Mediese Sentrum, Dr Ameen, en ons doen saam navorsing oor links- en regshandigheid in Suid-Afrika en die moontlike verband met vaskulêre assimetrie van die takke van die aorta boog.

Die inligting wat jy aan my beskikbaar stel, sal van waarde wees om my in staat te stel om hierdie navorsingsprojek te voltooi en die resultate sal ons begrip van die oorsprong van links- en regshandigheid noemenswaardig verhelder.

Hierdie onderhoud sal ongeveer sewe minute van jou tyd in beslag neem. Alle inligting sal streng vertroulik gehou word. Jou inligting sal volgens ‘n kode gestoor word, en jou identiteit sal deurgaans tydens die navorsingsprojek anoniem bly. Jou CTA skanderings sal slegs deur my en medici hanteer word. Indien enige voorheen onopgespoorde anatomiese abnormaliteite tydens die CTA analise opgespoor word, mag die vertroulikheid verbreek word in soverre die neuroloog dan die abnormaliteite en moontlike behandeling daarvan met jou mag bespreek. Daar is geen ander verwagte risiko’s verbonde aan jou deelname nie.

Deelname is vrywillig. Indien jy besluit om nie aan die studie deel te neem nie of op enige tydstip aan die studie onttrek, mag jy dit doen sonder enige gevolge hoegenaamd.

Stem jy daartoe in om aan hierdie studie deel te neem? ...

...

Dankie.”