EVALUATION OF PSEUDOCONTINUOUS ARTERIAL SPIN LABELING TECHNIQUE IN 1.5 T MRI: A PHANTOM STUDY

By

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CERTIFICATE

This is to certify that the dissertation entitled 'Evaluation of Pseudocontinuous Arterial Spin Labeling Technique in 1.5 T MRI: A Phantom Study' is the bona fide record of research work done by Norain Liyana Yusoff, Matric Number: P-IPM0066/14 during the period of September 2014 to June 2015 under the supervision. This dissertation submitted in partial fulfillment of the requirement for the Degree of Master of Science (Medical Research). Every research work and collection of data belongs to Advanced Medical and Dental Institute, Universiti Sains Malaysia.

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Main Supervisor,

Dr. Rafidah Zainon.

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LIST OF ABBREVIATIONS

ASL	Arterial Spin Labeling
CBF	Cerebral Blood Flow
MRI	Magnetic Resonance Imaging
ROI	Region of Interest
ICA	Internal Carotid Artery
PET	Positron Emission Tomography
CT	Computed Tomography
DSC-MRI	Dynamic Susceptibility Contrast Magnetic Resonance Imaging
SNR	Signal-to-noise ratio
pASL	Pulsed Arterial Spin Labeling
cASL	Continuous Arterial Spin Labeling
pcASL	Pseudocontinuous Continuous Arterial Spin Labeling
RF	Radiofrequency
VSASL	Velocity Selective Arterial Spin Labeling
GRASE	Gradient and Spin Echo (GRASE)

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ABSTRACT

The routine use of arterial spin labeling (ASL) in diagnosis various brain pathology still facing challenges in image acquisition, post processing and analysis of MR images. The application of ASL technique is still much limited in various clinical settings due to relatively lower sensitivity and image coverage compared to other existing method. This study is to review this advanced technique in Magnetic Resonance Imaging (MRI) with the fabricated phantom using pseudocontinuous ASL (pcASL) with better SNR. pcASL is also used in most hardware setup of MRI scanners. The main imaging parameters such as field of view (FOV), slice thickness (ST) and matrix size were evaluated to obtain optimal image acquisition. The T1, T2 weighted images and BRAVO sequences were also investigated in this study. A fabricated flow phantom was scanned with 1.5 T MRI scanner (GE system). Various labeling parameters were evaluated to obtain optimal image quality. The blood mimicking solution was prepared with a combination of 40 % glycerol and 60 % distilled water. The MR image quality was evaluated by measuring the the signal-to-noise ratio (SNR) of each image. The pcASL showed that it provides optimal SNR by applying optimal imaging parameters. The highest SNR value (94.9) was obtained in paediatric carotid artery size and 75 % stenosis with imaging parameters: slice thickness 9 mm, FOV 320 mm x 320 mm and matrix size 256. This study also found that some susceptibility artifacts can be found in the images. This is due to the turbulent flow inside narrow tubes or leakage inside the phantom. Many SNR cannot be obtained due to artifacts. Thus, familiarity with commonly encountered artifacts is important in determining the interpretation of image. Improvement of the SNR in pcASL measurements is crucial so that it could take a more central role in MRI studies.

ABSTRAK

Rutin penggunaan arteri pelabelan spin (ASL) dalam diagnosis pelbagai patologi otak masih menghadapi banyak cabaran dalam pemerolehan imej, pemprosesan dan analisis terutamanya dalam aliran darah serebral. Tujuan kajian ini adalah untuk menyiasat teknik canggih baru ‘pseudo-continous ASL (pcASL)’ dengan fantom yang direka menggunakan 1.5 Tesla MRI. Parameter utama seperti medan pengimejan (FOV), ketebalan hirisan (ST) dan saiz matriks telah diuji untuk mendapatkan perolehan imej yang optimum. Di samping itu, T1, T2 imej dan teknik BRAVO juga telah dinilai. Artifak imej juga adalah penting untuk dalam menentukan tafsiran imej. Dalam kajian ini, phantom tersebut telah diimbas dengan menggunakan 1.5 T MRI (sistem GE). Pelbagai parameter pelabelam diuji satu per satu bagi membolehkan imej yang terbaik untuk ditangkap dan dibandingkan. Kandungan darah ditiru dengan menggunakan gabungan gliserol dan air masing-masing pada jumlah 40 % dan 60 %. Nisbah isyarat-kepada-hingar (SNR) bagi setiap imej juga dikira. ASL telah menunjukkan bahawa ia juga boleh memberikan jumlah munasabah SNR. Nilai tertinggi (94.9) ditangkap di phantom yang mempunyai saiz arteri kanak-kanak dan 75 % stenosis dengan parameter: ketebalan hirisan 9 mm, FOV 320 mm x 320 mm, dan saiz matriks 256. Banyak SNR juga tidak dapat diperolehi kerana masalah artifak. Antara penyebab artifak adalah disebabkan oleh tiub yang sempit dan kebocoran di dalam phantom. Kajian ini memberi tumpuan kepada teknik pelabelan arteri berputar secara berterusan (pcASL). Objektif utama kerja yang dibentangkan dalam disertasi ini telah memberi tumpuan kepada mendapatkan parameter yang terbaik untuk digunakan dalam

teknik pcASL. Penambahbaikan nilai SNR untuk ASL adalah penting supaya ia boleh mengambil peranan yang lebih penting dalam kajian Pengimejan Resonans Magnetik (MRI).

CHAPTER I

INTRODUCTION

1.1 ARTERIAL SPIN LABELING (ASL)

Magnetic Resonance Imaging (MRI) is an important diagnostic tool that can assess brain structure and its function (Smith, 2014). Arterial spin-labeling (ASL) technique can quantitatively measure the cerebral blood flow (CBF) by using the arterial water as a tracer and it is completely non-invasive method without any needs of injectable contrast which is more suitable for patient with significant renal insufficiency. This ASL technique has become increasingly popular in clinical settings to evaluate and diagnose various brain disorders. It is safer without radioactive tracer and needs a shorter preparation and scanning time compared to radionuclide-based imaging assessment methods (A.R. Deibler *et al*., 2008). The non-invasive technique of ASL MRI will provide as an alternative to the needs of injectable tracers without compromising the results (Tracy R. Melzer *et al*., 2011).

Perfusion is defined as the blood delivery from artery to capillary network of living cells. In MRI, there are two main methods to measure the perfusion which are arterial spin-labeling (ASL) and dynamic contrast-enhanced MRI (DCE-MRI). ASL uses water in the living cells as an endogenous tracer, while DCE-MRI will need a paramagnetic tracer injection to measure the signal changes (Sourbron, 2010). In ASL MRI, the hydrogen protons from the arteries in neck region are inverted and after a while allowing the labeled protons reaching brain tissue, images will be captured. This is called as labeled image. Control images also will be captured to get perfusion weighted images when subtracting them with labeled images (Jill B. De Vis *et al*., 2013).

Perfusion-sensitive images are obtained by inverting or saturating water protons in the blood vessels that supply the region of interest (ROI), usually the neck. Then, the intensity changes in the brain can be measured. The saturation or inversion step is known as labeling or tagging. Spin labeling can be done by introducing a radiofrequency (RF) pulse over the imaging slab. After labeling, a post-label delay takes place that will allow the labeled protons to reach the slice of interest, leave the blood vessels and perfuse the tissue (Anne C Zappe *et al*., 2008).

The general application of ASL MRI is not limited to brain but also other main organs such as lungs and kidney. Cerebral blood flow (CBF) also important to be measured in patients before and after pharmacological interventions (John A. Detre and Alsop, 1999). Any obstruction in the internal carotid artery (ICA) will lead to decrease in perfusion pressure in the brain circulation (R.P.H. Bokkers *et al*., 2008). Any disturbance in blood flow can result in oxygen level reduction which is very crucial in brain cells. Thus the unique structures of various collateral blood vessels help to minimise the damage. As a result of occlusion of the ICA, blood flows through the alternative routes including Circle of Willis or leptomeningeal and ophthalmic collaterals. This will increase the transit times of labeled blood to the brain cells (R.P.H. Bokkers *et al*., 2008).

The studies of ASL in multiple delay times have been performed by R.P.H. Bokkers and colleagues in patients with symptomatic ICA occlusion. They were able to identify the brain regions which were impaired and quantify the arterial blood inflow using ASL

(R.P.H. Bokkers *et al*., 2008). This can help in accuracy of diagnosis as the centre which is affected more can be localised and the treatment can be more specified. The origin of the emboli for example can be clearly located after reviewing the brain perfusion map. ASL MR imaging has been able to give valuable information in term of hemodynamic function as compared to normal MR protocols. The association between the vessels structure, tissue perfusion and also brain function can be further asses (Peter Jan van Laar *et al*., 2008).

This study is to review this advanced technique in MR imaging with the fabricated phantom. As we know, the application of ASL technique is still much limited in various clinical settings. We hope to familiarise his technique in our center and gain as much knowledge on using ASL technique. The ASL method will be used to scan images from a phantom of blood vessel mimicking tube with different diameters and stenosis. The obstruction of the brain blood vessels are the main factor in determining the outcome of stroke patients. The carotid arteries when severely obstructed can lead to acute ischemic stroke which resulted in damaged in brain cells due to lack of oxygen. The effect of brain function is directly dependent on the area of blood vessels occlusion. Thus, fast and correct diagnosis is very crucial in determining patient's survival and disability outcomes. ASL can provide valuable information as it directly measures the CBF which is also the value of oxygen exchange in tissues.

The effects of arterial tagging on distal images can be quantified in terms of tissue perfusion because the regional changes in signal intensity are determined by blood flow and T1 relaxation. The tracer for spin-tag imaging is magnetically labeled water, which will decay during T1 of blood (approximately 1200 ms at 1.5 T) (A.R. Deibler *et al*, 2008). This allows for quantification of regional perfusion without the administration of exogenous tracers or arterial blood sampling (Chalela *et al*, 2000). In addition, structural images of brain can also be collected at the same time. It is also the best method to show the area of decreased CBF compare to normal CBF in the grey matter region (Donahue *et al*., 2102). As for cancer patients, ASL is very useful in the selecting and evaluating the therapies. This is because brain tumour mainly very aggressive and by determining the perfusion information, it will help the medical team to decide the best treatment for their patients (Petersen *et al*. 2014).

1.2 OBJECTIVES

1. To evaluate the new advanced technique of pcASL with fabricated phantom using 1.5 Tesla MRI.

2. To obtain the best parameters in using pcASL technique in order to get optimal image.

3. To gather image and data by testing different parameters of MRI sequences including PCASL, T1 and T2 weighted image and BRAVO.

4. To test the scanner compatibility with the pcASL protocol with flow phantom.

CHAPTER II

LITERATURE REVIEW

2.1 Arterial Spin Labeling.

Arterial spin labeling (ASL) technique is introduced since 10-15 years ago and has gained popularity in clinical perfusion imaging. Many research studies are able to prove its potential use in clinical world. It is soon will be a routine MR imaging sequence as it is non-invasive that will make it much safer. Thus, the familiarities of users with ASL technique will help in patient diagnosis and treatments in the future (Jeffrey M. Pollock *et al*., 2009). Many studies data has shown that ASL gave stable noise characteristics over the entire frequency spectrum, which makes it really suitable in studying low-frequency events in brain function (Jiong Jiong Wang *et al*., 2003). The purpose of ASL technique is to produce a flow-sensitized image (known as a labeled image) and a control image in which the static tissue signals are identical. This can be achieved by inverting or saturating the water protons in the blood supplying of captured area (Esben Thade Peterson *et al*., 2006). Figure 2.1 shows how the labeled and control image obtained during scanning. Arterial blood water is magnetically labeled at the labeling plane. After some time, the tracer flows into slice of interest and exchanges with tissue water. Then an image is taken (called the tag image). The process is repeated without labeling the arterial blood to obtain 'control image'. The control image and labeled image are subtracted to finally get the perfusion image.

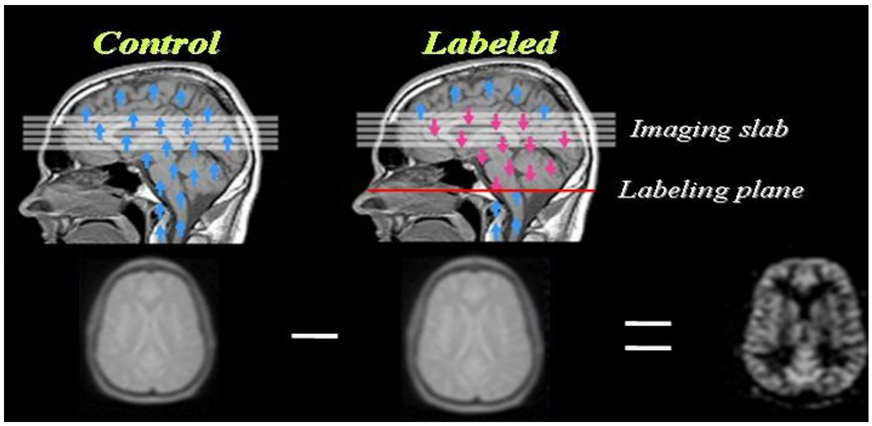

Figure2.1 Control and labeled image acquisition.
(Retrieved from Electronic Presentation Online System)

2.2 Cerebral Blood Flow.

Cerebral blood flow (CBF) is a really important because it can give value of the tissue viability, metabolism, and function. Dynamic measurements of CBF can show the mechanism of CBF regulation and also determine the dynamic behaviour of the neuron response by functional stimulation, drugs, or treatments (Kim *et al*., 1999). Some methods to study CBF include positron emission tomography (PET), computed tomography (CT) perfusion, MR perfusion (susceptibility weighted imaging or bolus tracking), single photon emission and xenon CT (Maldjia *et al*., 2011).

All these major techniques to measure CBF use exogenous tracers that can pass through arterial structure in the brain. Some of the tracers are very harmful to the kidney and could not certainly be used in paediatric patients. ASL will provide the CBF value in quantitative physiological units (mL blood/100 g tissue per minute) that suitable to use in longitudinal or multicenter studies (Patrick W Hales *et al*., 2014). ASL technique can be used in repeated times to track CBF changes in critical patients. ASL magnetically labeled water molecules in the arterial blood vessels. This is totally different from perfusion measurements using gadolonium bolus tracking in dynamic susceptibility contrast magnetic resonance imaging (DSC-MRI), or PET (positron emission tomography). The usage of exogenous contrast agents can be a very big problem in patients with renal disease and paediatrics population (Clark *et al*., 2013).

2.3 Different types of ASL.

The ASL technique has two main subcategories called pulsed ASL (pASL) and continuous (cASL). cASL has higher signal to noise ratio (SNR) than pASL, but less available on commercial MRI scanners due to the requirement of long and continuous radiofrequency (RF) transmission. The latest technique in ASL is known as pseudocontinuous ASL (pcASL). It divides the long continuous radiofrequency (RF) pulse in cASL into multiple separates short pulses but eventually will have same labeling effects as cASL. As a result, better SNR is achieved compared to cASL and can be convenient to be used in most hardware setup of MRI scanners (Sung-Hong Park *et al*., 2013).

In pASL, a wider labeling area which located proximal to the imaging plane received single and short (2-5 milliseconds) RF pulses. pASL has several advantages with higher tagging efficiency, less power deposition and improved transit time for the labeled spins to travel from the labeling region to the imaging plane. But the main disadvantages in pASL are low SNR and increased transit delay (Maldjia *et al.*, 2011).

Some methods are also can be used to spatially select the labeling that will allow the perfusion distribution of single arterial territories to be measured. Velocity selective arterial spin labeling (vsASL) is being explored as a means of eliminating arterial transit time dependence. The recent technique known as time-resolved ASL has been developed as a noninvasive angiography method.

Figure 2.2 shows that in cASL and pcASL, the labeling plane is located at the base of brain region. At this region, a continuous RF pulse is used to label the arterial blood before it traveled up to cerebral arterial network higher up (imaging volume). While in the pASL the labeling slab received short RF pulses in larger area which includes tissue and arterial blood.

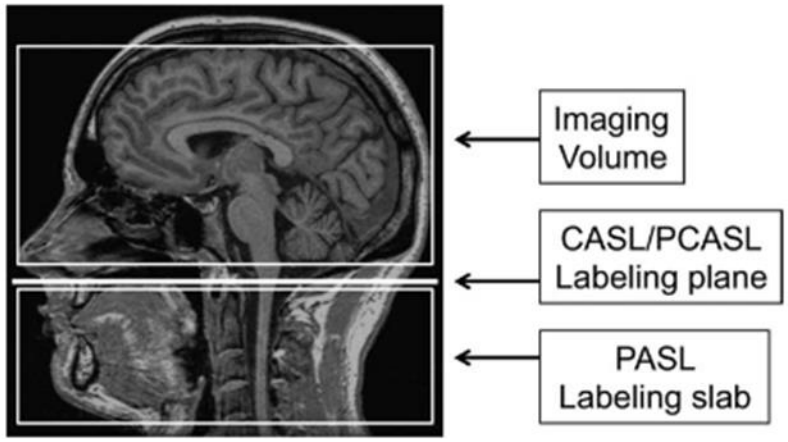

Figure 2.2 Schematic diagram of imaging and labeling regions for CASL/PCASL and PASL. In CASL/PCASL, labeling occurs as blood flow through a single labeling plane, while in PASL, a slab of tissue, including arterial blood, is labeled.
(This image retrieved from article: Recommended Implementation of Arterial Spin; Labeled Perfusion MRI for Clinical Applications: A Consensus of the ISMRM).

The measurement of perfusion value using ASL is done by inverting the longitudinal magnetisation of the arterial blood flow through the tissue, waiting for a given 'inflow time' (T1), then capturing an image (labeled image). Then, the same process is repeated but without labeling the arterial blood flow (controlled image). Perfusion of the region of interest is the result of subtraction between the 'labeled image' and 'controlled image' (Patrick W Hales *et al.*, 2014). Figure 2.3 shows how the process of ASL imaging started with labeling of arterial blood water at the base of brain region. Then after a short delay of time, the arterial blood water will exchange and perfusion process happen before finally acquisition of perfused tracer with brain tissues.

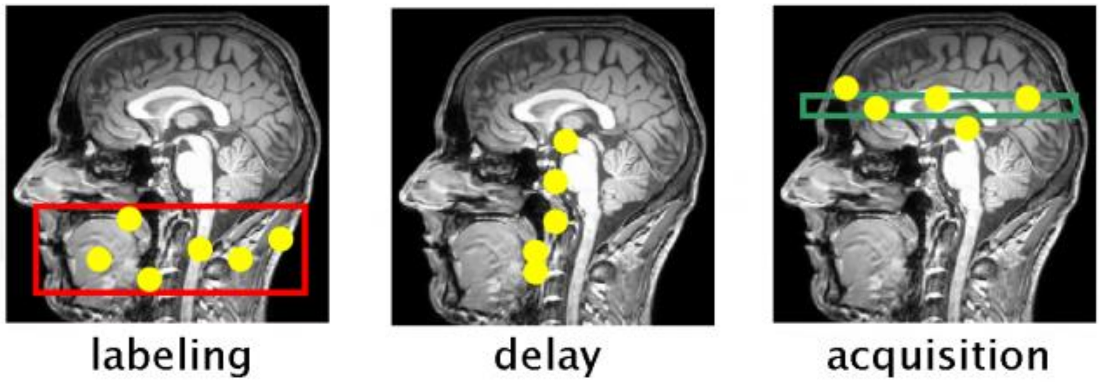

Figure 2.3.Image acquisition after allowing some time pass after labeling process. Image retrieved from website: www.irisa.fr/visages/activities/theme2/projects/asl.

2.4 Advantages of ASL.

Many imaging sequences also can be used to measure the changes in tissue magnetization due to ASL. Due to the effect of ASL is small; any imaging sequence with high SNR is applicable to be used. For example, many data using ASL has used echo-planar imaging due to its high SNR and speed. This will help in reducing the potential for motion artifacts between label and control scan images. But, the echo-planar imaging will cause distortions in regions of high static susceptibility gradients and degrade the quality of image.

Last several years, the 3D sequence based on fast spin echo or gradient and spin-echo (GRASE) has been introduced for image acquisition in ASL to improve image quality. It will improve SNR and can also help the use of background suppression pulses to reduce the static brain signal and increase sensitivity (John A. Detre *et al*., 2012). Most major clinical MRI settings are already installed with ASL sequences. It uses may vary with regard to the need for labeling, imaging, and quantification, but ASL can be definitely use together with other clinical imaging protocols. Although the main consideration for use is still in the brain imaging, it can later be extensively uses for other major organs. The clinical example is in cerebrovascular diseases which primarily affect the brain perfusion. Many earlier studies showed that ASL MRI was feasible in acute stroke. But, lacking in robust methodology, low sensitivity for hypo-perfusion, and long signal requirement limits its use. Until now, dynamic susceptibility contrast (DSC) perfusion MRI is still used predominantly in diagnostic tool for acute stroke (John A. Detre *et al*., 2012).

2.5 Limitations of ASL.

Active research is still going on in ASL technique but some limitations has been recognized. Firstly, in 1.5 T MR imaging unit, the theoretical perfusion-induced signal change is just 1% for gray matter and 0.4% for white matter. This can cause ASL signal disturbed by phenomena other than perfusion. Arterial signal artifacts, magnetisation transfer artifacts, and the influence of noise in the input images are such examples. Long radiofrequency (RF) pulses and multiple images acquisition also seems to be troublesome in the commercial scanners (Jackson *et al*., 2005).

ASL method have low signal-to-noise ratio (SNR), difficult to plan the process, and also doubt regarding cerebrovascular kinetics or blood equilibrium, directly affecting perfusion estimates. As many studies actively done combining with technical advances, ASL will become possible to use as the main diagnostic tool in clinical settings. Also, the variability of continuous ASL (cASL), pulsed ASL (pASL), and pseudo-continuous ASL (pcASL) sequences still need to be further understood (Sanna Gevers *et al*., 2011). The product sequence should be readily available from a vendor to make it easier to use in any clinical setting. The neurologic diseases which include steno-occlusive disease is rather difficult because of increased in arterial transit times (ATTs). It will need long delays between labeling and image capturing (>2 seconds). The signal of labeled blood decays over time and lower the SNR. So, multiple images acquisition are needed and averaging over multiple repetitions is not possible with all ASL sequences within reasonable acquisition times. To solve this issue, three-dimensional (3D) gradient and spin echo (GRASE) readout module is necessary. It can increase the SNR of a single measurement and scanning will be done in multiple times (Steve Z Martin *et al.*, 2014).

2.6 Susceptibility Artifact.

ASL also will have susceptibility artifact as on any echo-planar MR imaging sequence. It is represented as signal intensity void on ASL CBF maps. This may be caused by metallic hardware, blood products, calcification and air that surround the region of interest. It also represents a significant limitation of ASL in the evaluation of diseases because of magnetic distortion. Neurosurgical metal, such as orthodontic appliances and other materials also significantly disturb interpretation of ASL CBF maps by producing focally diminished signal intensity. Blood products can give local gradient susceptibility artifact and thus are seen as low signal intensity on gradient sequences, including ASL. This can be seen in hemorrhagic infarct type of stroke. Motion is also a common problem in most clinical MR examinations. Small amounts of motion can produce a significant source of error in clinical ASL. Motion artifact may produce increases or decreases in signal intensity on a focal or global basis (A.R Deibler *et al.,* 2008).

2.7 Clinical application of ASL.

ASL gives better spatial and temporal resolution compare to other current technique (Asllani., 2012). Stroke is ranked in third place of mortality cause in western countries. It also a major cause of disabilities that affect not only health but resulted in loss of financial source in single bearing families. A quarter of stroke is caused by lacunar infarction due to ischemia in the territory of the small perforating intracerebral arteries. The patients will have gait disturbance, dementia and also parkinsonian syndrome (H S Markus *et al*., 2000). These types of disabilities will surely affect patient's daily life. Immediate diagnosis and treatment are the major factors for patient’s outcome. Post-ischemic hyper-perfusion which commonly associated with cerebral infarction is both beneficial (i.e., prevent more infarct) and harmful (i.e., more edema and hemorrhage, and neuronal damage due to reperfusion injury). In addition, post-ischemic hyper-perfusion in the subacute stage (48 hours after onset) is linked with tissue necrosis. Thus, it is very valuable for the physician to able to measure the CBF accurately after stroke attacks (Yoji Tanaka *et al*., 2011).

Although ASL sequence used for scanning organs other than the brain is still very new but several studies has been done to measure myocardial blood flow (MBF) in human and animal models. Studies have been performed to demonstrate the effect of drugs to MBF in vasodilation. It can be an important diagnostic tool for detecting ischemic heart disease in early stage before a fatal heart attack occur (Hung Phi Do *et al*., 2014). ASL images also can show the regional cerebral blood flow (rCBF) that makes it possible to do direct physiological interpretation. This has lead to pharmacologic studies of various psychoactive drugs such as Citalopram and amphetamine. Prior to ASL technique, pharmacologic studies on brain often compared the brain activity on drug and brain activity off drug (Stephanie B. Stewart *et al*., 2014). The non-invasive method of ASL is really valuable for repeated CBF measurements in patient follow-up, pharmacologic studies as well as paediatric population. ASL is very useful in studying slow changes of brain function.

As compared to BOLD fMRI, ASL is more appealing and well suited for pharmacology MRI (phMRI) studies. This includes the direct pharmacological effects of drugs which can take effect over hours or days including measuring drug effects indirectly by their modulation of a stimulus or task response. ASL gives quantitative CBF measurement both at rest and during task activation which is critical in separating drug effects on resting brain with task-induced activation. This advantage of ASL technique have been recognised by the scientific research community with several review articles pointed out the value of ASL for assessing drug effects on baseline brain function. But, the main limitation for ASL such as limited availability, low signal to noise ratio (SNR), and image coverage still remains as the major obstacles (Danny J J Wang *et al*., 2011).

MRI is always the choice of technique use study the developing physiology of the brain. It is non-ionising and also has more spatial resolution make it the suitable method to look into the transition and development of brain from childhood, through adolescence and into adulthood. Reference range values can be developed using the hemodynamic properties of the ASL signal in healthy children and young adult that can be used as comparison to the abnormal cerebral perfusion pathologies. For example Sturge-Weber Syndrome which caused abnormality in intracranial venous, a cutaneous capillary angioma, and ocular deformation due to anomalous embryonic development. All of these conditions will lead to perfusion defects that lead to epilepsy and contralateral hemiparesis (Patrick W Hales *et al*., 2014). Follow ups of patients can be safely done with the ASL technique to look into the level of damage and appropriate treatment plan.

The wide application of ASL technique will include various types of diseases such as stroke, chronic vascular disease, dementia, and assessment of tumour blood flow. The latest approach in pseudo-continuous ASL (pcASL) with high SNR is showing good result to be used in clinical world. The pcASL will use advance magnetic field strength, multichannel coils, background suppression and improved labeling schemes. Studies by Wong manage to use this high SNR of the pcASL labeling scheme together with the flexibility of tagging arteries within a single plane. Different from the use of pulsed ASL (pASL), which require complex planning procedure to position a three-dimensional (3D) slab over vessels of interest (Thomas W Okell *et al*., 2013). The higher SNR value in pcASL is due to longer labeling period. However, the labeling efficiency will also decrease as the higher blood velocity risks the underestimation of increase in CBF (Esther Ah Warnert *et al*., 2014).

2.7 Direction in future research.

To enable more widespread use of ASL MRI in clinical practice, it is important to develop widely available MRI sequence and software analysis platforms. Future research is crucial in investigating its utilisation in various medical settings (Keith A Gillis *et al*., 2014). It is still perplexing that ASL MRI unable to found its way into routine clinical practice. This is due to multifactorial issues such as weak signals and ASL methodologies are somewhat seen as more complex than other MRI routine methods. Furthermore, ASL benefits also have been downgraded by more widely technologies that commonly available such as dynamic susceptibility contrast perfusion MRI and BOLD fMRI. Clinicians are also not familiar with being able to quantify CBF easily and thus rarely demand it. The availability of truly robust ASL MRI implementations and growing research in this area will help to more widespread use especially for the benefits of patient itself (John A.Detre *et al*., 2012). ASL surely can be applied in healthy populations and also on specific patient populations (Nederveen).

CHAPTER III

METHODOLOGY

3.1 Materials (The Phantom).

In this study, fabricated phantom is used. The body of the phantom used Perspex because it is solid, stable, non-hazardous, easy to handle and most important it mimic the real organ characteristics. The phantom is compact and also portable that can be well suited for reassembly in multi-center research setting.

This phantom was designed of inside the vessel modules. It included the adoption of two constituent geometries:

i. A set of straight tubes (adult: 0.8 cm and paediatric: 0.5 cm in diameter)

ii. A constant-diameter tube in the shape of a U-bend. It has stenosis of 75% and 50% each).

The straight tubes provide standard geometry for testing accuracy and precision as well as the effect of slice position and image resolution. The first straight tube with 0.8 cm in diameter represents adult’s carotid artery while the other straight tube with 0.5 cm in diameter mimics the pediatrics carotid artery. Basically the mimicking diameter of the carotid arteries were chosen as it capable of reproducibly generating the requisite flow rates and patterns.

The specifications of the phantom are as followed :

i. Dimension: 24 x 24 x 2.5 cm^3.

ii. Radius U-bend: 2.5 cm.

iii. Diameter U-bend: 5 cm.

iv. Diameter U-bend tube: 0.8 cm.

v. Diameter 1st straight tube: 0.8 cm.

vi. Diameter 2nd straight tube: 0.5 cm.

vii. 50% stenose: 0.4 cm.

viii. 75% stenose: 0.2 cm.

ix. Width: 24 cm.

x. Length: 24 cm.

xi. Length straight tubes: 17 cm each.

Figure 3.1 shows 2D design of phantom that is used during the studies. It has a Perspex base with 2 pairs of straight tubes and u-tubes. The straight tubes have different diameters that represent adult and paediatric arteries. The u-tubes have different percentage of stenosis at the distal ends. This phantom will be cut at the middle to fit the head coil of MRI scanner. Figure 3.2 and 3.3 show the cross section of the phantom in clearer view. It shows that the phantom has different diameters of straight and u-shaped tubes and is cut at the middle into two parts.

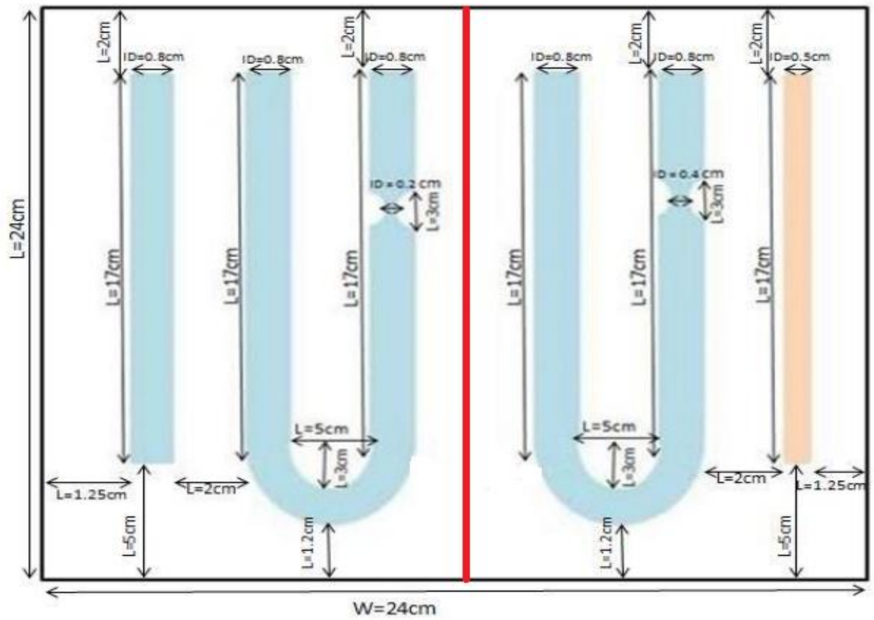

Figure 3.1: The 2D design of phantom (red line shows where it is cut to fit head coil of MRI).

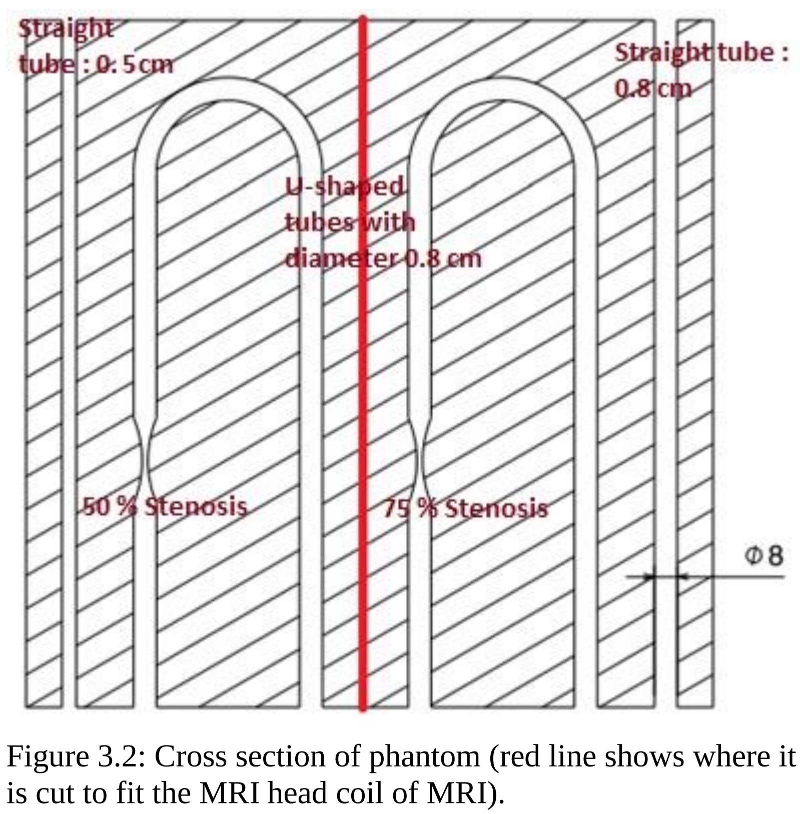

Figure 3.2: Cross section of phantom (red line shows where it is cut to fit the MRI head coil of MRI).

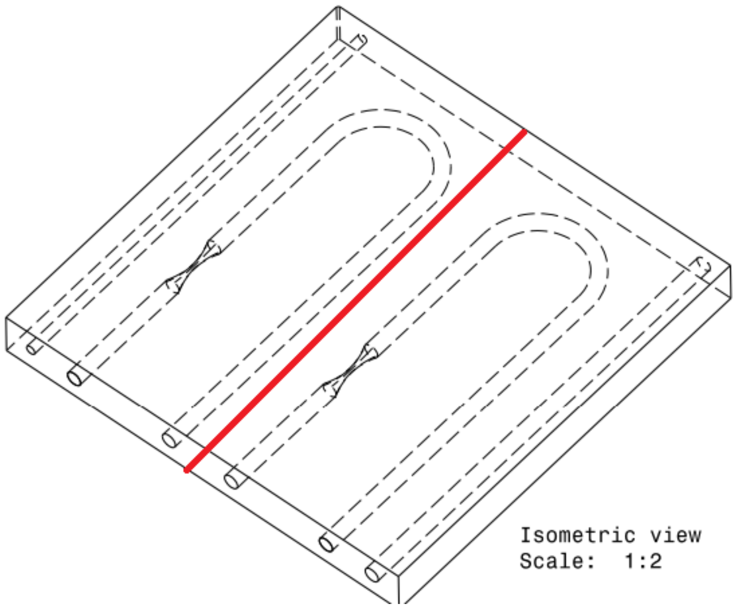

Figure 3.3: Isometric view of the phantom (red line shows where it is cut to fit head coil of MRI).

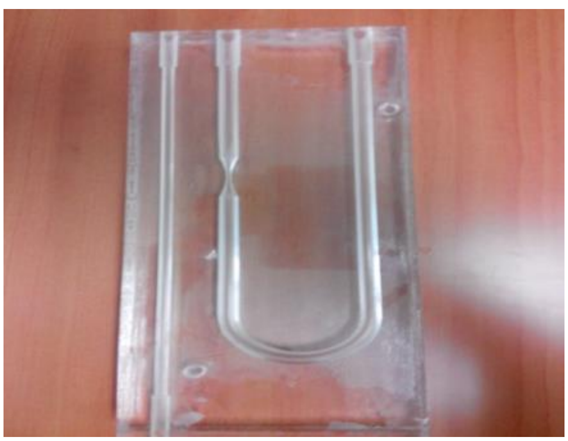

Figure 3.4: Phantom that is used during scan.

3.2 Procedure.

Assemble the phantom and assess performance

The blood is mimicked in the container by using combination of glycerol and distilled water 40% and 60% respectively. Water pump is placed in the container to pump the blood mimic into the phantom and circulate it during the experiment. The pump is connected to the joint plastic pipes which are the combination of one T-shape pipe, and two L-shape pipes which made two holes for blood mimic to flow into the phantom. These holes are connected with plastic tubes which affiliated with phantom at one end of U-tube and one end of straight tube. Other plastic tubes are connected from another one end of U-tube and one end of straight tube for blood mimic flow out from phantom to blood mimic container. This container is placed outside the room. The phantom is set up as figure below:

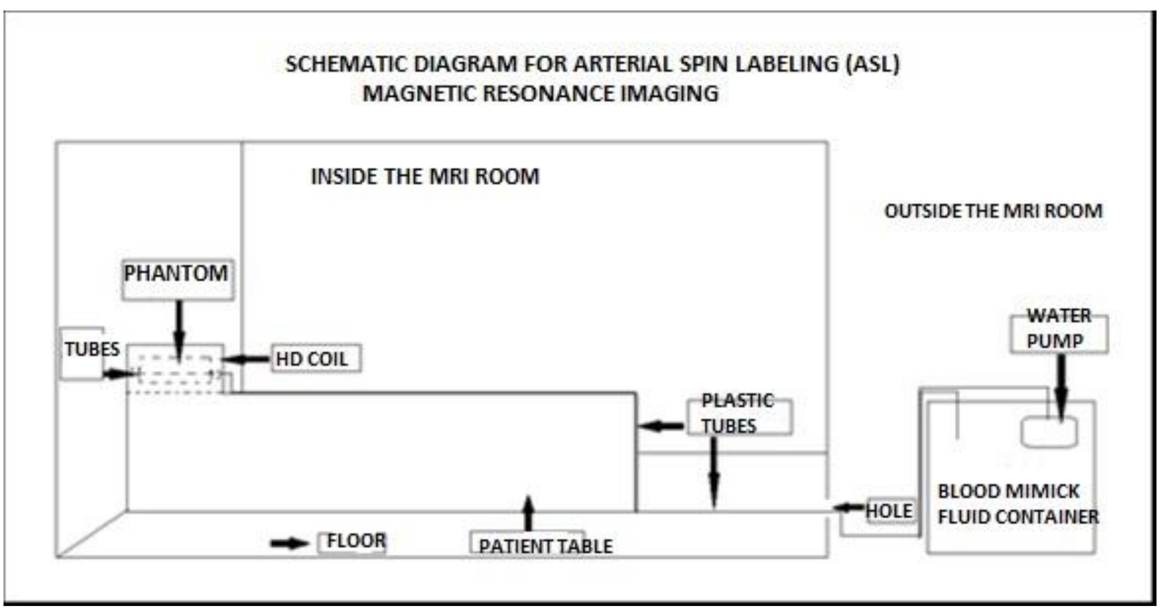

Figure 3.5: The schematic diagram for setting up ASL phantom.

The water pump is switched on and make sure that there is no bubble in the tubes and phantom during circulation of blood mimic. The phantom and tubes are checked to make sure there is no leakage. The velocity of blood mimic is measured to make sure it is close to reference with 75 cm/s for adult and 97 cm/s for paediatric. The velocity is measured by calculating how long the mixture travels in certain distance of tube. Colour dye is used to clearly visualise the distance of blood mimic fluid travel from starting of connector tubes to it ends. The lengths of the tubes are 25 cm each. So we will divide the length of tubes (25 cm) with the time we get for the dye travel in the tubes. This method will be repeated using different colour of dyes in order to get the mean value.

Figure 3.6 shows the real environment inside the MRI room when the phantom has been connected to plastic tubes and placed inside the head coil of MRI scanner. The tubes are then put through a hole inside the wall in between scanner room and the computers outside to the water pump in water container.

Figure 3.6: Phantom assembly inside the MRI room.