OSIPI Open Science Initiative for Perfusion Imaging

OSIPI Task force 4.1: ASL lexicon

Milestone #1:

Standard ASL techniques and parameters in brain perfusion imaging

Organization of this document

This document aims to organize comprehensive lists of standard terminology for ASL techniques and parameters, including acquisition protocol and output parameter maps. Throughout the document, the following nomenclature is used:

- **Parameters:** Parameters are the quantities of interest of the ASL perfusion imaging and analysis. Output parameter maps are derived from the input dataset.
- **Attributes:** Attributes are technical quantities or descriptions related to the imaging, analysis or pre-processing procedures. They define the performed steps of extracting parameters maps from the input dataset.

Within each individual section, parameters/concepts are organized into tables, where each parameter/concept should correspond to a single row in a table, with following items to be listed if applicable:

- **Name:** A unique name for the parameter or attribute.
- **Notation:** If applicable, a commonly used abbreviation.
- **Description:** A short definition or specification; if available, a mathematical formula will be utilized as it provides a unique description of the quantity, regardless of varying nomenclature and interpretation.
- **Dimension:** If applicable, the general physical units.
- **Reference:** To the literature establishing the concept or corresponding analysis method and providing relevant details. If applicable the publication first introducing the respective technique is cited. For general concepts and quantities, review papers will be cited which give an overview of the general concept.

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OSIPI Open Science Initiative for Perfusion Imaging

General classification

This document for "standard ASL techniques and parameters in brain perfusion imaging" complies with the consensus paper for brain ASL by the Perfusion Study Group of the International Society for Magnetic Resonance in Medicine (ISMRM) and the EU-COST action 'ASL in dementia' (Alsop et al., 2015), as well as ASL-BIDS Extension Proposal which is currently being developed.

The basic structure of standard ASL sequence (generic definition)

In this section, the basic structural elements of the standard ASL sequence are listed and defined. Detailed description about the basic principles of ASL can be found in several excellent technical review articles, e.g. (Golay et al., 2004) (Wong, 2005) (Alsop et al., 2015) (Barker et al., 2010).

Name	***Description***
Arterial Spin Labeling (ASL)	Any MRI technique in which contrast is generated by manipulation of the arterial blood magnetization using RF pulses prior to image acquisition.
Labelling pulse	ASL-preparation, which consists of a single short RF pulse or pulse-train. In general, it is applied proximal to the imaging volume/slices and inverts the magnetization of arterial blood flowing into the imaging volume/slices.
Control pulse	Control pulse consists of a single (or two) pulse or pulse-train, that makes equivalent Magnetization Transfer (MT) effects on the static tissue as compared to the Labelling pulse, but without leading no labeling of arterial blood flowing into the imaging volume/slices.
Labelled image	Image acquired after preparation by a labelling pulse.
Control image	Image acquired after preparation by a control pulse.
Delay Time	The time interval between the labeling and image acquisition that allows the labelled arterial blood to reach the tissue of interest. Called Post-Labeling Delay (PLD) in pseudo-continuous ASL (pCASL) and Inversion Time (TI) in Pulsed-ASL (PASL). See the section "Parameters in ASL labeling module" below for a more detailed definition.
Single PLD/TI	ASL protocol in which images are acquired with a single delay time.
Multiple PLD/TI	ASL protocol in which images are acquired with multiple (more than one) delay times.

Background suppression	Background suppression aims to reduce the signal fluctuation on the subtracted delta-M image (i.e. noise) by suppressing the signal intensity of the static tissue, which is achieved by the use of additional RF pulses, usually inversion pulses applied during the delay time.
Pre-saturation	Saturation of the imaging volume/slices is performed just before (and/or after) the label and control pulses to minimize any residual label/control differences from magnetization transfer (MT) and/or slice profile effects. WET (Water suppression enhanced through T1 effects) pulse (Ogg et al., 1994) with four pulses is widely used (Golay et al., 2005).
Vascular Crushing	Vascular crushing is designed to reduce signal present in larger arterial vessels at the time of imaging. Generally, it is achieved by applying crushing gradients after the excitation pulse, which selectively dephases signal based on the velocity of the spins in the direction of the gradient.
M0 image	Calibration image required for CBF quantification, used to estimate the M0 of blood. It needs to be acquired in addition to the labelled and the control images when background suppression and/or pre-saturation pulses are applied. When background suppression and pre-saturation pulses are not applied, the (mean) control image can be used as the M0 image. The methodology used to derive the blood M0 from the M0 image is described here.

Standard ASL Labeling Attributes

Name	***Notation***	***Description***	***References***
Continuous ASL	**CASL**	A single labelling RF is applied over a long period, typically 1-3 sec, which continuously inverts arterial blood as it flows through a specified labeling plane. Flow-driven adiabatic inversion is used for labelling.	(Alsop et al., 2015)
Pseudo-continuous ASL	**pCASL**	Similar to CASL, labeling occurs over a long period, typically 1.5-2 sec and inverts flowing arterial blood. In pCASL, however, a train of short RF	(Dai et al., 2008) (Alsop et al., 2015)

		pulses applied at a rate of approximately one per millisecond replaces the single, continuous label of CASL. Flow-driven adiabatic inversion is used for labelling. Note that the consensus/simplified quantification of CASL and PCASL are identical.	
Pulsed ASL	**PASL**	A single (or limited number of) short RF pulse (typically 10-20 ms) is applied to 'instantaneously' invert a slab of arterial blood magnetisation.	(Alsop et al., 2015)
Echo-Planar Imaging and Signal Targeting with Alternating Radiofrequency	**EPISTAR**	Variation of PASL, in which the label is performed by a slab-selective adiabatic inversion pulse applied proximal to the imaging volume/slices. The control preparation is achieved by applying RF pulses with total power matched to the labeling inversion pulse (to generate the same MT effects across the imaging volume) but which result in minimal perturbation of the arterial blood longitudinal magnetisation e.g. two consecutive inversion pulses with half power.	(Edelman & Chen, 1998)
Flow-Sensitive Alternating Inversion Recovery	**FAIR**	Variation of PASL, in which the label is performed by a non-slice-selective global inversion pulse, while the control image is obtained by a volume/slice-selective inversion pulse applied at the imaging slice. Because of this symmetric nature, FAIR allows inflow of the labelled blood from both sides of the imaging slice.	(Kim, 1995)

Quantitative Imaging of Perfusion Using a Single Subtraction II	**QUIPSS-II**	QUIPSS-II aims to control the bolus duration in PASL, minimize the varying arrival time, and allow reliable quantification of CBF by using PASL with single TI. This is achieved by applying a saturation RF slab to the area where the labeling RF slab is applied and saturating the "tail" of the labeled bolus. See "Bolus duration" for the definition.	(Wong et al., 1998)
QUIPPS II with thin-slice TI_1 periodic saturation	**Q2TIPS**	Modified version of QUIPSS-II, aiming to improve the saturation efficiency by replacing the QUIPSS-II saturation slab by multiple thin saturation RF pulses applied at the distal edge of the labeling RF slab.	(Luh et al., 1999)
Proximal Inversion with Control for Off-Resonance Effects	**PICORE**	Variation of PASL, in which the label is identical to that of EPISTAR, while the control image is obtained by an off resonance inversion pulse that is applied at the same frequency offset as the label, but without applying slab-selective gradient. See "Bolus duration" for the definition.	(Wong et al., 1997)

Parameters in ASL labeling module

Name	***Notation***	***Dimension***	***Description***
Labeling duration	LabDur τ	sec (BIDS), ms (usual)	For CASL/pCASL. Duration of the constant CASL labeling RF or pCASL labeling pulse train. See Figure-1.
Bolus duration	BD	sec (BIDS), ms (usual)	For PASL. Temporal width of the labelled bolus of spins, defined as the time from the end of the

			labeling pulse to the centre of the first QUIPSS-II/Q2TIPS pulse.
Post-labeling delay	PLD	sec (BIDS), ms (usual)	For CASL/pCASL. Time from the end of the labelling train to the excitation pulse of the image acquisition. In multi-slice acquisition, this is applied to the firstly acquired slice. See Figure-1.
Inversion time / Inflow time	TI	sec (BIDS), ms (usual)	For general PASL. Time from the labelling pulse to the excitation pulse of the image acquisition. In multi-slice acquisition, this is applied to the firstly acquired slice. See Figure-1. BIDS uses the term post-labeling delay also for PASL.
	TI_1	sec (BIDS), ms (usual)	For QUIPSS-II/Q2TIPS. Time from the labeling pulse to the bolus saturation pulse. In Q2TIPS, it is to the 1st saturation pulse. See Figure-1.
	TI_2	sec (BIDS), ms (usual)	For QUIPSS-II/Q2TIPS. Time from the labeling pulse to the excitation pulse of the image acquisition. This value is equivalent to TI of the conventional (non-Q2TIPS) PASL. See Figure-1.
TI_1 stop	TI_{1s}	sec (BIDS), ms (usual)	For Q2TIPS. Time from the labeling pulse to the last bolus saturation pulse. See Figure-1.
Background suppression (pulse) timing	BS_1 to BS_n	ms	For background suppression scheme. Time from the labeling pulse (in pCASL, from the start of the labeling) to the Nth background suppression pulse. See Figure-1.
Vascular crushing velocity	V_{enc}	cm/s	Minimum velocity of labeled protons, signal of which will be 'removed' from the image
	b	s/mm^2	
Labeling plane offset / distance		mm	For pCASL, this is the distance between the centre of the imaging volume and the center of the labelling plane
Labelling slab gap		mm	For PASL, this is the nominal gap between the leading edge of the labelling slab and the closest edge of the the imaging volume

Labeling Pulse Average Gradient		mT/m	For pCASL. The non-zero mean gradient in the z-direction that produces the flow-driven pseudo-adiabatic inversion. See Figure-2.
Labeling Pulse Maximum Gradient		mT/m	The amplitude of the gradient applied during the labelling pulse in pCASL labeling pulse train. See Figure-2.
Labeling Pulse Average B1		µT	For (p)CASL, the average B1-field strength of the RF labeling pulses, could explain systematic differences between sites. See Figure-2.
Labeling Pulse Flip Angle		degree (°)	The flip angle of a single labeling pulse in pCASL labeling pulse train.
Labeling Pulse Interval		ms	For pCASL. The interval between two successive pCASL labeling pulses. See Figure-2.
Labeling Pulse Duration		ms	For pCASL. The duration of each pCASL labeling pulse. See Figure-2.
Labeling Slab Thickness		mm	For PASL. The thickness of the labeling RF slab.
Slice time		ms	For a 2D multi-slice acquisition scheme, the time between the excitation pulses of successive slices
Repetition time	TR	ms	The time from a labeling/control pulse to the next control/labeling pulse

Figure 1

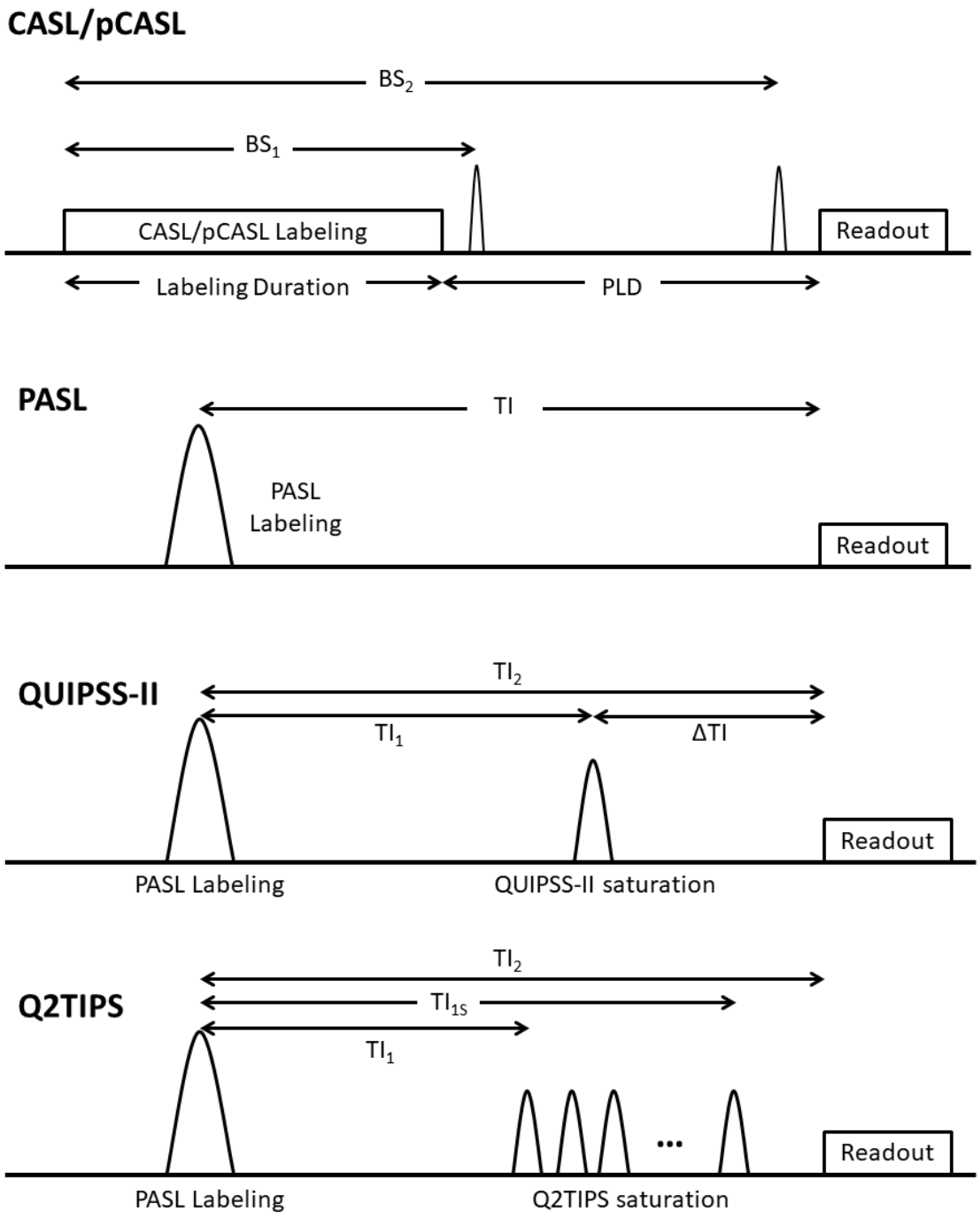
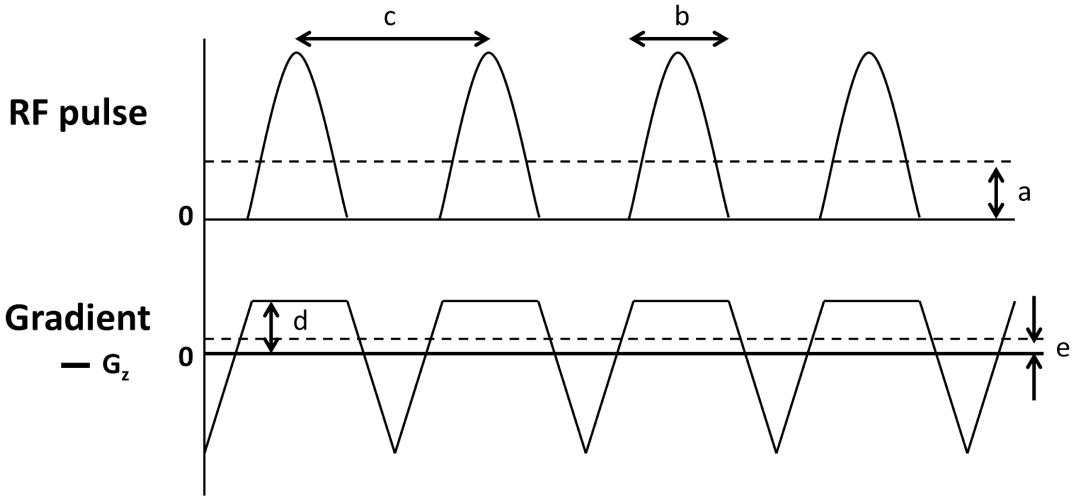

CASL/pCASL
BS2
BS1
CASL/pCASL Labeling
Readout
Labeling Duration
PLD
PASL
TI
PASL
Labeling
Readout
QUIPSS-II
TI2
TI1
ΔTI
Readout
PASL Labeling
QUIPSS-II saturation
Q2TIPS
TI2
TI1S
TI1
...
Readout
PASL Labeling
Q2TIPS saturation

Figure 2



a: Labeling Pulse Average B1
b: Labeling Pulse Duration
c: Labeling Pulse Interval
d: Labeling Pulse Maximum Gradient
e: Labeling Pulse Average Gradient

Readout Attributes

Name	***Notation***	***Description***
Echo-Planar Imaging	EPI	One of rapid imaging techniques, in which an excitation pulse is followed by acquisition of multiple k-space lines by switching the readout gradient polarity rapidly. In single-shot EPI, all k-space lines are collected after a single excitation pulse. In multi-shot EPI, collection of k-space lines is segmented into multiple shots.
Gradient and Spin Echo	GRASE	A hybrid technique of Gradient Echo and Spin Echo. An excitation pulse is followed by several refocusing pulses (similar to Fast/Turbo Spin Echo), and after each refocusing pulse, gradient echoes are collected by rapidly switching the readout gradient polarity (similar to EPI).

Stack-of-spirals	SoSP	Non-cartesian 3D acquisition techniques, in which the readout is performed in a spiral trajectory in the kx-ky space in each kz partition. Single-shot (RARE) or multi-shot (FSE).
Number of segments/shots	N_{seg}	For a 3D acquisition scheme in which k-space is acquired over multiple separate scans, this is the number of scans acquired.

Note:

ASL derivative parameters

Name	*Notation*	*Unit*	*Description*
ASL difference image Perfusion-weighted image Delta M (ΔM)		a.u.	Image obtained by subtracting the labelled image from the control image, which subtracts out the static tissue signal and consequently shows the perfusion signal produced by ASL-preparation.
Cerebral Blood Flow	CBF	mL/100g/min	Quantity of blood (mL) reaching 100g of tissue per unit of time (min)
Arterial Transit Time Arterial Arrival Time Bolus Arrival Time	**ATT** AAT BAT	ms	Time between when blood is labelled at the labeling plane and when that labeled blood first arrives at the imaging voxel/slice. Note that ATT, ATT and BAT are dependent on the technique used to label the blood (e.g. location of the labelling), and it is therefore not generally comparable across studies.

Note:

References:

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